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ABSTRACT

This fifth in a series of seven modules for a course titled Nondestructive Examination (NDE) Techniques I explains the radiographic process, from radiation source selection to equipment and specimen selection and arrangement, and film processing. The module follows a typical format that includes the following sections: (1) introduction, (2) module prerequisites, (3) objectives, (4) notes to instructor/student, (5) subject matter, (6) materials needed, (7) procedures, (8) data table, (9) reference materials, (10) test. (The course is one of fifteen technical courses for the second year of a two-year postsecondary curriculum in Nuclear Quality Assurance/Quality Control Technology.) (LRA)

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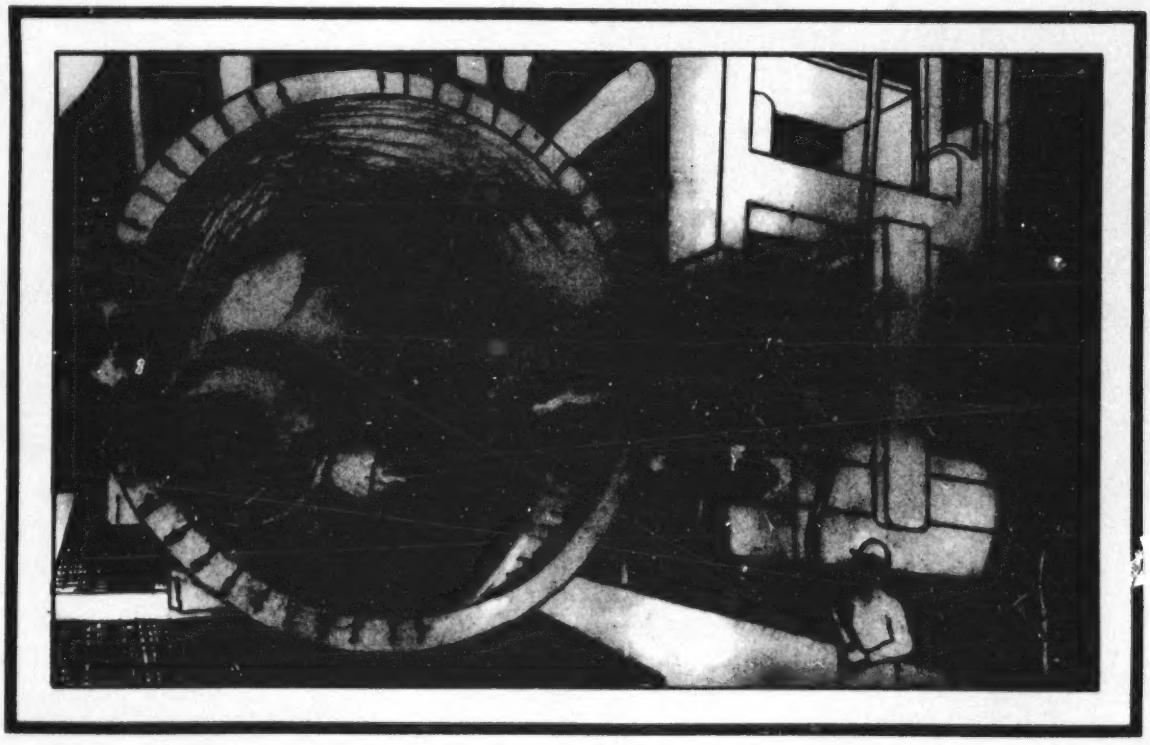
NUCLEAR TECHNOLOGY

COURSE 26 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES I

MODULE 26-5 Fundamentals of Radiography



CE 024 250

GENERAL PHYSICS CORPORATION
Columbia , Maryland

COURSE MODULES

COURSE 26 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES I

Module 26-1 Visual Tests
Module 26-2 Leak Tests
Module 26-3 Hydrostatic Tests
Module 26-4 Liquid Penetrant Tests
Module 26-5 Fundamentals of Radiography
Module 26-6 Radiography Inspection
Module 26-7 Radiographic Specifications and Code Requirements

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This module was prepared for General Physics Corporation by Richard Groseclose, General Physics Corporation.

GENERAL PHYSICS CORPORATION

1979

INTRODUCTION

Radiography is a nondestructive examination method widely used in the nuclear power industry. QA/QC technicians who are qualified in this test method are typically employed by fabricators and manufacturers of nuclear-grade components, plant constructors, electric utilities, and organizations which provide plant maintenance, modification, repair, and training services. The qualified QA/QC technicians may be responsible for one or more of the following:

- performance of radiographic test
- evaluation of test results
- witness of test
- supervision of other test personnel

Radiography is a process of testing materials that uses penetrating radiation such as X-rays or gamma rays. A photographic film is exposed to such rays that have passed through a specimen, is processed, and forms a permanent record of the resulting image. This process, thereby allows examination of the interiors of objects that are opaque to light. The basic essentials for producing a radiograph are:

- radiation source
- object to be examined
- photo-sensitive film

The radiation sources used in industrial radiography produce ionizing radiation, which may penetrate the human body and produce serious damage to cells and body tissue. Personnel working with radiation producing equipment and materials must be familiar with such radiation sources, methods of radiation detection and measurement, and the methods of controlling personnel exposure.

This module explains these concepts and describes the radiographic process, from radiation source selection, to equipment and specimen selection and arrangement, and film processing.

This module is prequisite for Module 26-6, Radiographic Inspection, which discusses specific applications and useage, and Module 26-7, Radiographic Specifications and Code Requirements, which discusses the interpretation and evaluation of radiographs.

MODULE PREREQUISITES

The student/trainee must have a background which includes general high school mathematics and Algebra I. Completion of Course 1, Radiation Physics and Course 2, Radiation Protection I are also very useful for better understanding of these module materials.

OBJECTIVES

Upon completion of this module, the student/trainee should be able to:

1. Answer correctly applicable questions on topics covered in this module as selected from the Level II SNT-TC-1A certification written test. Note: the topics and information needed to prepare the student/trainee for the SNT-TC-1A test which are not covered in this module, are covered in modules 26-6 and 26-7.
2. Answer correctly with a score of 80% or better a set of written exercises covering the following topics:
   (a) particulate and electromagnetic radiation
   (b) gamma radiation sources
   (c) X-ray sources
   (d) radioisotope source and capsule characteristics
   (e) radioisotope cameras and accessories

(f) X-ray machine characteristics
(g) radiation detection and measurement equipment
(h) equipment calibration

3. Demonstrate a knowledge of the operation and usage of radiation detection and measurement equipment by pointing out and identifying on illustrations or actual devices the various controls, and explaining the method of operation and usage in actual practice.
4. Explain the principles of radiation safety as related to time, distance, and shielding, and define the following terms: roentgen, rem, and rad.
5. Given information such as radioisotope or X-ray dose rate and shielding values, calculate:
   - emission or dose rate at a given distance
   - dose rates at different distances
   - half-value layers of shielding required to meet radiation intensity requirements at specific distances
6. Explain geometrical unsharpness as related to the location of the source, specimen, and film.
7. Define the following:
   - film contrast
   - subject contrast
   - film density
   - H & D curve
   - film speed
   - film graininess
8. Study selected specimens that are to be radiographed and specify the following:
   - source and film selection orientation and method of placement
   - penetrameter selection and usage
   - specimen identification method
   - overlap and number of exposures
   - shielding
   - use of screens and filters

9. Describe the radiographic film developing process. Outline the steps involved, and state approximate dwell times for each step.
10. Describe methods of reducing scatter.
11. Demonstrate an understanding of personnel safety and radiation protection by reviewing a sketch and description of a typical radiographic test set-up, and list the following:
    - recommended dosimetry
    - personnel precautions
    - calculated permissible "stay times" in radiation areas identified
    - effect of shielding usage specified

SUBJECT MATTER

Sources of Radiation

There are two main types of radiation: "particulate" radiation, which is composed of small particles moving through space, and "electromagnetic" radiation, which consists of very short electromagnetic waves. Both kinds of radiation convey energy through space.

Particulate radiation is the movement of subatomic particles through space. The particles of particular interest in this course are listed below with their characteristics.

Alpha:

- a particle identical with the nucleus of Helium atom (two protons and two neutrons)
- electrical charge, +2
- atomic mass, 4
- usually emitted from the nucleus of a large atom, such as Uranium
- travel at relatively low speed, through only a few centimeters in air and may be stopped by a sheet of paper

Beta:

- a particle identical to a high speed electron
- atomic mass, 1/1,840 of a proton
- emitted as either a Negatron, electrical charge -1, from a nucleus with excess neutrons, or as a Positron, electrical charge +1, from a nucleus with excess protons.
- travel at high velocities, approaching the speed of light, with a range of several feet in air, and may be stopped with a thin sheet of aluminum or a few sheets of paper.

Neutron:

- a particle with about the same mass as a proton, but with neutral electrical charge
- very penetrating, can be stopped by absorption in water, paraffin or boron
- not normally emitted in natural radioactive decay
- emitted from light elements such as beryllium and lithium when bombarded with alpha particles
- absorption by the nuclei of other elements produces radioactive isotopes.

Electromagnetic radiation consists of very short electromagnetic waves of energy having no mass or weight, moving with the speed of light (186,000 miles per second). Such radiation may be described as small packages of energy called photons or quanta. It has some properties of particles, but also has a characteristic wave motion, wavelength and frequency. For all electromagnetic radiation, the product of frequency and wavelength is a constant, and, when proper units are used, equals the speed of light. The intensity of the energy emitted depends on the frequency or wavelength of the radiation: high frequency radiation has high energy, while low frequency radiation has low energy. Two types of high energy electromagnetic radiation, gamma and X-, are used extensively in the radiographic nondestructive testing process. These are described as follows:

Gamma Radiation:

- originates in the nucleus of an atom
- emitted by the disintegration of radioactive material such as Iridium - 192 or Cobalt - 60
- highly penetrating, very high energy

X-Radiation:

- produced when a stream of fast-moving high-energy electrons are slowed down upon striking a suitable target such as tungsten
- energy level variable and controllable

Gamma Ray Sources

Radioisotopes or "sources" for industrial radiography use are available from:

- Naturally occurring materials, such as Radium - 226
- Fission products, such as Cesium - 137
- Activation from neutron bombardment, such as Iridium - 192 or Cobalt - 60.

In gamma-radiography, since all of the radioactive material in the source is producing gamma rays, the source must be as small as possible to obtain maximum sharpness of film image. The other desired characteristics for the source material are:

- appropriate gamma energy to penetrate the specimen
- high specific activity which would give small source size and high emissivity, and
- long half-life

The gamma energies emitted and half-life are physical constants for each isotope; therefore, the appropriate isotope must be selected for the particular class of work.

Several terms that have been introduced relating to radiation sources, and terms that will be discussed are defined as follows:

- Activation: the process by which neutrons bombard stable atoms to make them radioactive
- Radioisotope: an unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

- Gamma energy: gamma radiation emitted from radioisotopes, measured in Mev (Million electron volts)
- Specific activity: degree of concentration of radioactive material within a gamma ray source. Usually expressed as curies per gram or curies per cubic centimeter.
- Emissivity: the energy emission rate, usually expressed as Roentgen/Curie/Hour @ 1 ft. (R/Ci/Hr@1ft.)
- Roentgen: unit of exposure dose of ionizing radiation. One Roentgen (R) equals the amount of gamma or X-rays required to produce 2.5×10^{-9} coulomb of electrical charge per kilogram of dry air at standard conditions.
- Curie: basic unit of intensity of radioactivity in a sample of material. One curie (Ci) is equal to 3.7×10^{10} disintegrations per second, or approximately the activity from 1 gram of radium.
- Half-life: the length of time in which half the atoms in a radioactive substance disintegrate; the length of time required for the activity to decay to one-half its initial strength.

Table 26-5-1 lists characteristics of gamma sources most used for industrial radiography.

Encapsulation of Radioisotopes

In gamma radiography, the energy emitted from decaying nuclei is used to penetrate test specimens and expose a radiographic film. The radiography equipment must be designed to permit the gamma rays to escape, but the radioactive source material must be contained and not released into the environment where the chemicals could contact or enter the human body. This containment is accomplished by sealing the radioactive materials in small capsules - a process called "encapsulation".

The following factors must be considered in the selection of materials and designs of capsules:

- Resistance to corrosion from the radioactive material contained.
- Damage to capsule material caused by the emitted radiation.
- Resistance to high or low temperature regions in which the capsule is to be used.
- Resistance to erosion or abrasion.
- Resistance to structural stresses such as impact, vibration and fatigue loading.
- Sealing technique, e.g., silver brazing, shielded arc welding, electron beam welding, etc.
- Wall thickness of the capsule shall be as thin as practical designs allow to minimize radiation absorption by the walls.

Early capsule designs used threaded plugs, adhesives, crimping and soldering techniques for sealing which were frequently inadequate and leaked in service. Contemporary designs, however, usually incorporate fusion welding to effect a durable seal. See Figure 26-5-1, "Capsule Designs".

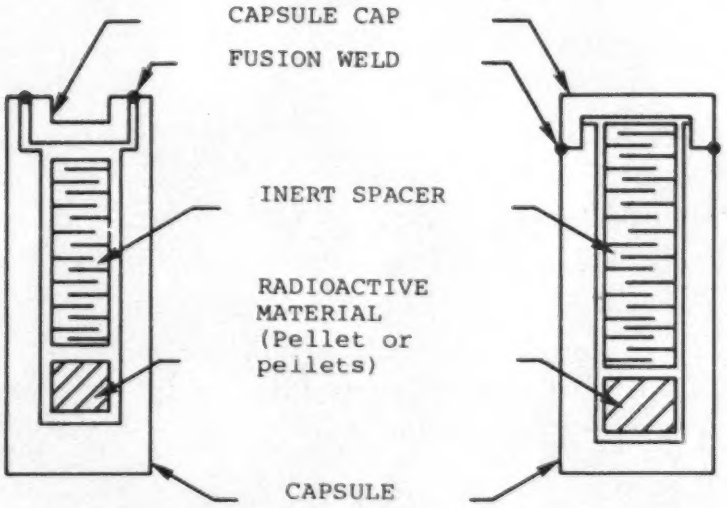


Figure 26-5-1. Capsule Designs

Metallic source pellets such as cobalt, iridium, and thulium are furnished in the shape of a right circular cylinder with typical dimensions as shown in Table 26-5-1. As the table indicates, the diameter and length are usually equal; this shape permits the use of any surface as the focal spot, since all surfaces, as viewed from the test specimen, are approximately equal in area.

TABLE 26-5-1. Typical Metallic Pellet Dimensions

Diameter	Length
1 mm.	1 mm.
1/16 in.	1/16 in.
1/8 in.	1/8 in.
1 cm.	1 cm.

Cesium and other compound type sources consist of a finely divided material which is more difficult to contain than the metallic pellets. Such sources are usually double-encapsulated, or encased in two individually sealed capsules. See Figure 26-5-2, "Double Encapsulation".

After a capsule is sealed, a leak test is required to determine if the closure is acceptable. No leakage will be permitted; if the sealing is not properly done, the by product material may escape and contaminate other equipment and the working area. Following a satisfactory leak test, the source exterior surfaces must be decontaminated and inspected carefully before being placed in service.

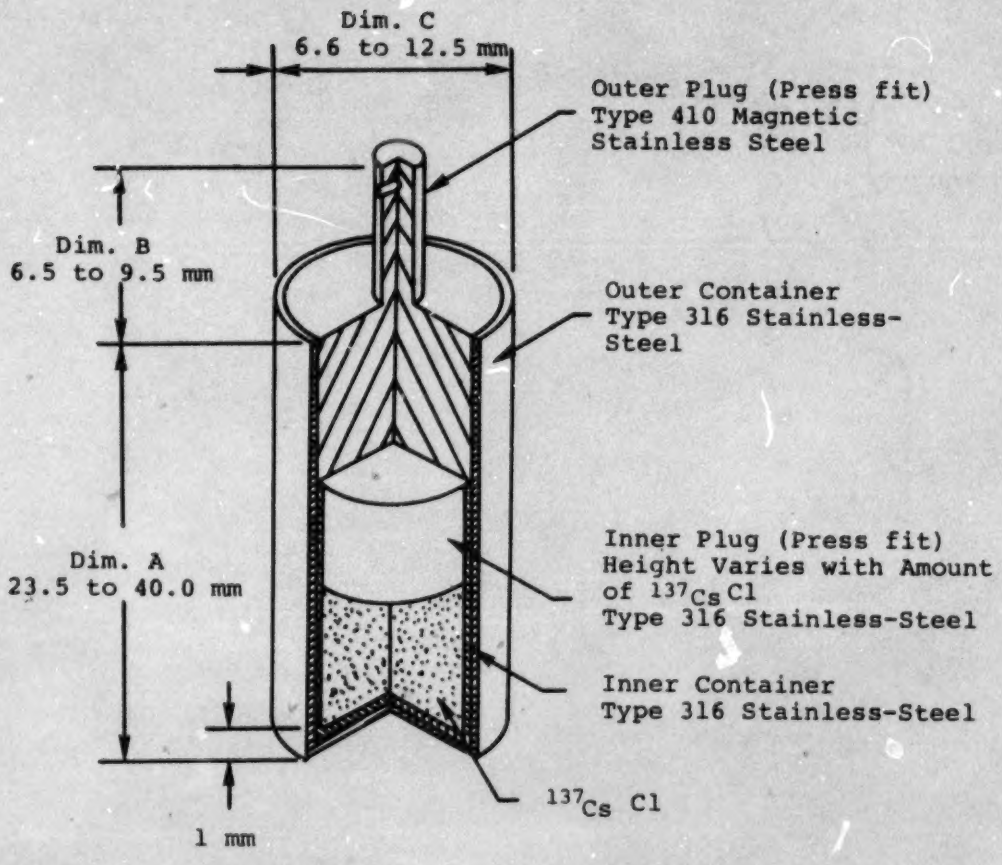


Figure 26-5-2. Double Encapsulation

Isotope Cameras

Isotope sources present a full-time radiation hazard and consequently, must be handled carefully, and stored and locked in shielded containers when not in use. The equipment designed to provide a means of safe handling and secure storage of radioactive source, together with a source, is referred to as a camera. A typical camera is shown in Figure 26-5-3.

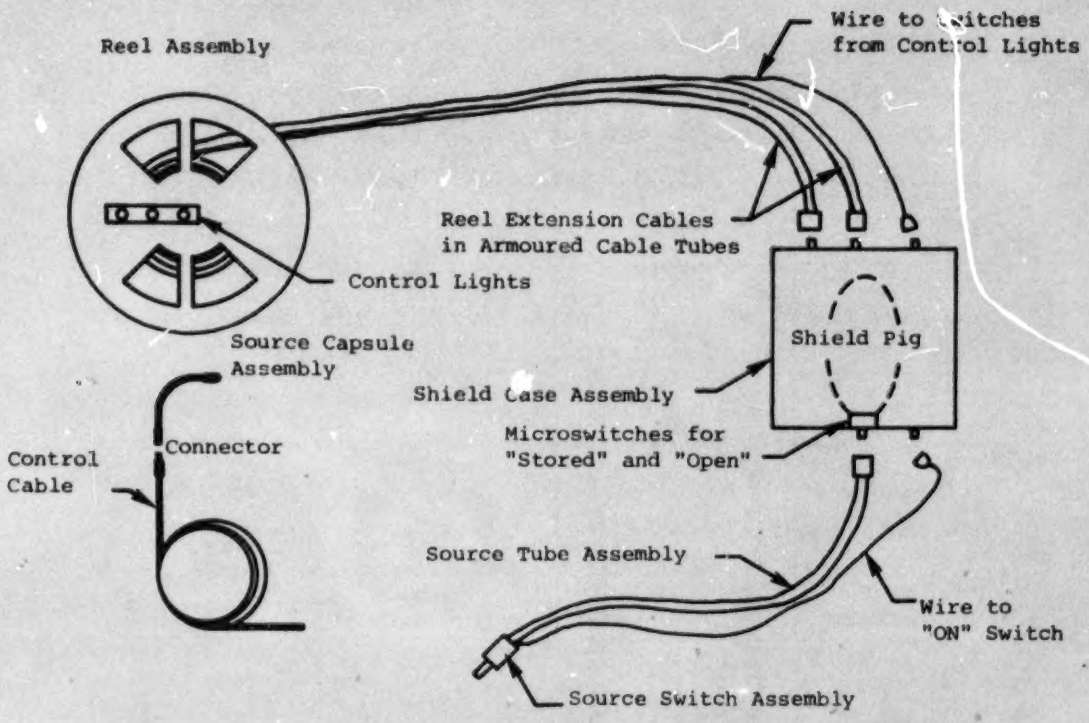


Figure 26-5-3. Isotope Camera

The basic components of the camera are:

- Source capsule assembly: A short length of flexible cable with the source, in a stainless steel capsule, attached to one end, and with a connector for attachment to the control cable on the other.
- Shield case assembly: A heavy gage steel case containing lead or spent Uranium shielding material for storing the source capsule when not in use. One side of the case has connectors for the attachment of the control cables and the other a connector for the source tube assembly.

- Reel assembly: A storage reel for the flexible armored steel cables, a crank to extend and withdraw the source, and control lights to indicate source positions: "stored" (safely stored within the shield pig), "Open" (partially extended), and "On" (fully extended in the source tube).
- Source switch assembly: A housing containing a microswitch, located at the extreme end of the source tube assembly, which functions to energize the "On" control light when the source is in the fully extended position.

Operation of the isotope camera is illustrated in Figure 26-5-4.

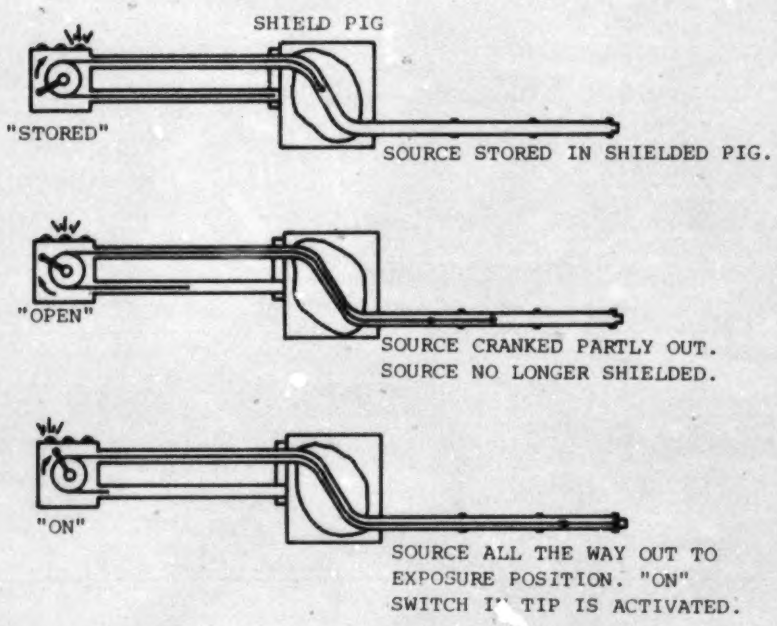


Figure 26-5-4. Camera Operation

The camera described operates with manual control, and may have a direct reading indicator of the length of cable extended to indicate source position. Cameras are also available with the same basic shield pig design, but with pneumatic or electrical drive units replacing the manual crank. Other types may also be obtained that do not require source removal from the pig, but permit exposure by the removal or re-orientation of a part of the source shielding.

X-Ray Sources

The basic requirements for the generation of X-rays are: a source of free electrons, a means of moving the electrons rapidly in the desired direction, and a suitable target material for the electrons. The X-ray tube supplies these requirement. In addition to the tube, an electrical power supply is required for supplying current to heat the tube filament for producing the electrons, and a high voltage source for accelerating the electrons toward the metal target. A basic X-ray tube is illustrated in Figure 26-5-5, "Diagram of an X-ray Tube".

The tube basically consists of two electrodes, the cathode and the anode, enclosed in a heavy, high vacuum envelope of heat resistant glass. A focusing cup surrounds the filament (cathode) to help direct the emitted electrons toward the target (anode). A dense target material with a high melting point, such as tungsten, is required to assure a maximum number of collisions while withstanding the high heat of X-ray generation. The area of the target struck by the stream of electrons is called the focal spot.

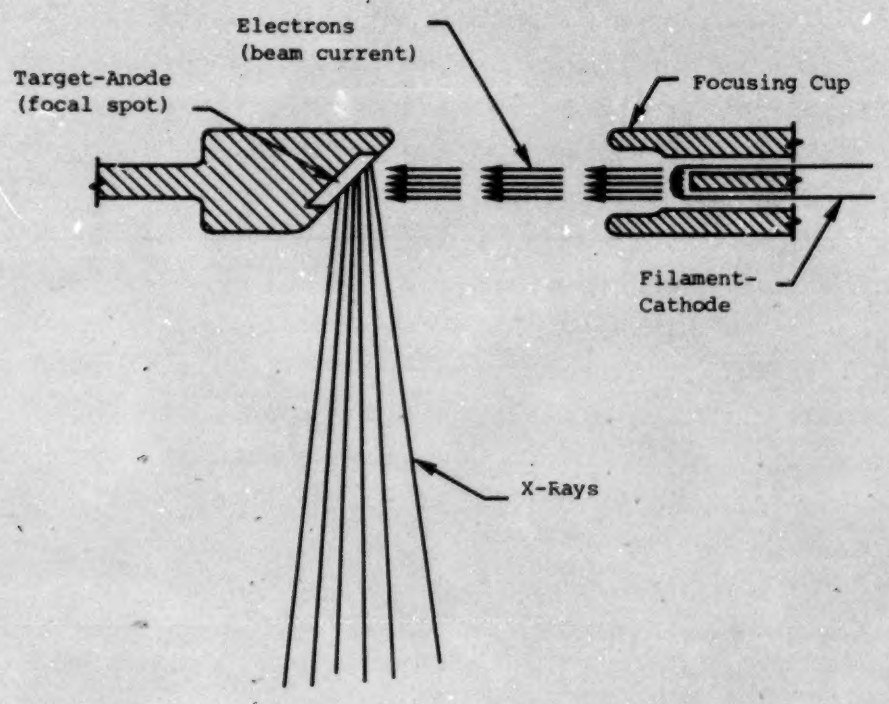


Figure 26-5-5. Diagram of an X-Ray Tube

Filament power is furnished by a small low voltage transformer delivering a current of several amperes. A high voltage transformer provides voltage between the filament and the target. The higher the voltage, the greater the speed of the electrons to the target. High speed electrons produce X-rays of shorter wavelength and higher penetrating energy than do low speed electrons.

Most of the energy of the electron beam is expended in the production of heat. To avoid the destruction of the tube anode, the heat must be dissipated. Medium and low power tubes have a thermal conducting metal rod connected to the anode which conducts heat from the target to outside

cooling fins. High power tubes have hollow anodes with a circulating water or oil system for heat removal. The duty cycle of the equipment (percentage of exposure time versus total time) is determined by the rate of anode cooling. The efficiency of the X-ray equipment is therefore limited by the efficiency of its cooling system.

X-ray tubes are rated by the voltage applied to the anode. Typical low-energy level X-ray machines may have tube voltages from 10,000 to 100,000 volts (10kV to 100kV). High energy machines may be rated at millions of volt. A characteristic of high-voltage radiography is that it is applicable to comparatively thick or highly absorbing specimens. X-ray machines designed for industrial applications have the approximate practical specimen thickness limits shown in Table 26-5-2:

TABLE 26-5-2. Industrial X-Ray Machine Applications

X-RAY KV	APPROX. PRACTICAL SPECIMEN THICKNESS LIMITS
50	Woods, plastics, thin light metals
100	2-inch Aluminum
150	1-inch Steel, 4½-inch Aluminum
250	2-inch Steel or Equivalent
400	3-inch Steel or Equivalent
1000	5-inch Steel or Equivalent
2000	9-inch Steel or Equivalent

X-ray intensity is not exactly proportional to tube current because the voltage and waveform of an X-ray machine transformer varies with the load.

Radiation from an X-ray tube may be considered to consist of two parts. These are referred to as the continuous X-ray spectra and the characteristic X-ray spectra. Electrons in the beam impinging on the target material and some electrons ejected from the target atoms give up kinetic energy as they strike nuclei of target atoms. The loss of energy results in X-rays. Since these electrons have a wide range of velocities, the X-rays generated cover a wide band of wavelengths. The wavelength depends upon the energy given up by the electron. This provides a continuous spectrum of X-rays and is the radiation most used industrial radiography. The characteristic X-rays are those resulting from the displacement of orbital electrons in the target material. This radiation is of a specific wavelength, "characteristic" of the element making up the target material, and of relatively small energy compared to that of the continuous spectrum.

Refresher on Radiation Detection and Measurement

Radiation coming from radioactive materials or X-ray producing equipment cannot be detected by man using only his senses. The body may be penetrated by intense radiation and severely damaged without feeling pain until some time later when radiation sickness develops or other biological effects are observed. Instruments must therefore be used to detect and measure radiation which poses such a threat.

The term detection refers only to the determination of the presence of radiation, whereas measurement includes both detection and quantitation of the radiation present.

Radiation measuring instrument usually provide a measurement of dose or a dose rate. The measurement of dose refers to the accumulated radiation exposure dose over a period of time, and dose rate refers to the immediate level of radiation intensity.

The Roentgen (R) is the unit of radiation exposure which is based on the ionizing effect of gamma or X-radiation passing through air. As applied in measuring occupational exposure, this is a rather large unit, so the millircentgen (mR) is frequently used for measuring small doses (1R = 1,000 mR).

Dosimeters

Dosimeters are instruments which measure total dose exposure. Dosimeters are usually used by workers in areas exposed to radiation. The dosimeter indicates, at any time, the total radiation dose received to that time. Examples of dosimeters include:

- Lauritsen Electroscope

This dosimeter consists basically of an ionization chamber for collecting the ions formed by penetrating radiation, with an insulated central electrode with one fixed and one movable part. Initially, the electrode is charged; the electrode parts, having the same electrical charge, are repulsed by a force proportional to the charge on the electrode, and the movable part (or quartz fiber) is deflected accordingly, a distance proportional to the charge on the electrode. As rays enter the chamber, ions of the opposite electrical charge are formed in the air, move toward and collide with the electrode, and neutralize an amount of charge on the electrode. As the radiation-ionization process continues, the electrode is discharged appreciably, and the change in position of the movable quartz fiber indicates along a linear scale graduated in Roentgen or milliroentgen units. When the unit is charged initially, the voltage is adjustable and sufficient to deflect the quartz fibre to coincide with the zero mark on the scale when viewed through the eye-piece. See Figure 26-5-6:

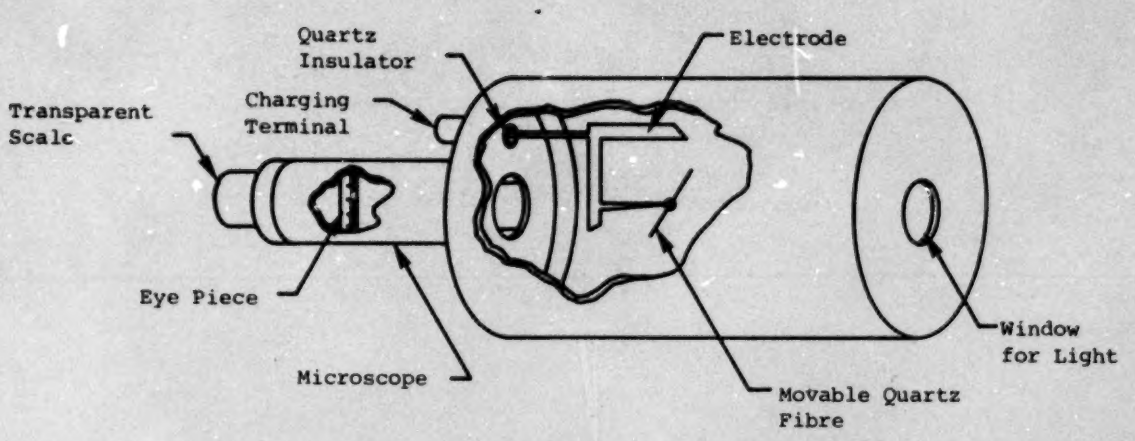


Figure 26-5-6. The Lauritsen Electroscope

- Self Reading Pocket Ionization Chamber (PIC) Dosimeter

The PIC dosimeter is also a quartz-fiber ionization chamber instrument, similar to the Lauritsen Electroscope, but of the compact size of a large fountain pen. The electrode consists of two U-shaped quartz fibers, one fixed and one movable. The fibers are fused together at the ends of the U, and a small microscope is focused on the opposite end of the movable fiber. A transparent scale appears in the lens system, with the most frequently used scale graduated 0-200 mR. See Figures 26-5-7 and 26-5-8.

- Film Badges

Until recently, the film badge was usually the official record of whole-body radiation exposure. The film badge is a small plastic or metal holder designed to hold a photographic film packet similar to those used by dentists for X-raying teeth. The film packet contains two pieces of film, one relatively sensitive

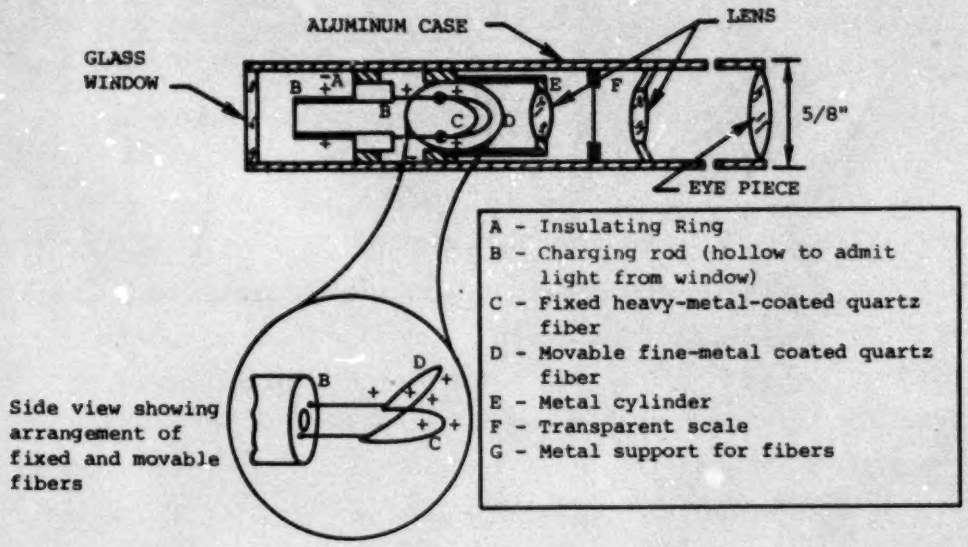
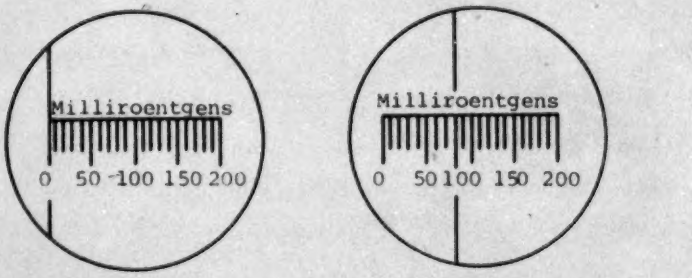

ALUMINUM CASE
LENS
GLASS WINDOW
5/8"
EYE PIECE
A - Insulating Ring
B - Charging rod (hollow to admit light from window)
C - Fixed heavy-metal-coated quartz fiber
D - Movable fine-metal coated quartz fiber
E - Metal cylinder
F - Transparent scale
G - Metal support for fibers
Side view showing arrangement of fixed and movable fibers

Figure 26-5-7. Self-Reading Pocket Ionization Chamber (PIC)



Fully charged, "Zeroes" Condition.

Indication after exposure to 80mr ionizing radiation

Figure 26-5-8. Typical Pocket Dosimeter Scales

to radiation, covers a range of 10mR to 5,000 mR, and the other, relatively insensitive, covers a range of 400 mR to 600,000 mR. Ions produced by radiation in the film emulsion activate the silver molecules in the emulsion. When the film is developed, these activated silver atoms are reduced to elemental silver and turn black. A measurement of the "blackness", or density, of the film is a measure of the radiation dose received. The holder also includes small circles or squares of several metals (absorbers) to help determine the doses contributed by different energy groups of gamma radiation. The blackness of the film varies behind the different absorbers, because radiation of different energies will vary in penetrating ability through the respective absorbers. Evaluation of these areas on the film provides a more accurate determination of dose.

- Thermoluminescent Dosimeter - "TLD"

Most industrial users have replaced film badges with "TLD's" for providing an official record of whole body radiation exposure. Thermoluminescent is that property, of a previously excited material, to phosphoresce or give off light upon heating. Thermoluminescent materials, such as lithium fluoride or calcium fluoride are used in "TLD" badges; after exposure to radiation, the material gives off light when heated. The total quantity of light emitted is proportional to the amount of radiation which interacted with the material. TLD's have several advantages over film badges, such as greater stability, sensitivity and accuracy, and small size for use in measuring extremity exposures.

- X-ray Film

When using X-ray film for radiation monitoring, faster film is usually used for personnel monitoring and slower film is used for area monitoring.

Survey Meters

The instruments and devices described above all measure radiation exposure, but cannot be used effectively to make a rapid survey of an area. Instruments are needed to measure radiation intensity instantly; two such types of instruments are available - ionization chamber instruments with amplifier systems, and Geiger counters. Both types detect and measure gamma and X-radiation, and are used extensively for radiography work.

- Ionization Chamber Instruments

Instruments of this type measure high levels of radiation, usually up to 1,000 R/hour. Typical instruments have a meter with a scale reading from 1 to 1000, with a selector switch permitting reading mR/hour or R/hour.

The instrument operates in the following manner: When exposed to a radiation field, ionization occurs in a gas in an ionization chamber. The ions formed move to an electrode having the charge of opposite sign. The ions strike the electrodes, which are connected to an electrical source, are neutralized, and cause a small electrical current flow. The current flow is amplified, measured and interpreted in terms of the radiation intensity required to produce the ionization.

The accuracy of instruments of this type is plus or minus 15 percent, making them unsuitable for precision measurements, but they provide instantaneous measurement.

- Geiger-counters

Geiger-counters or Geiger-Mueller detectors are usually low level instruments and read only to about 50 mR/hour. They have a tendency to "block-out" in a high radiation field, and show only a small reading above zero due to background radiation. The user should be careful, therefore, in accepting a zero or near zero reading as meaning no radiation is present.

Geiger-counters derive their greater sensitivity from the "gas-amplification" characteristics of the Geiger tube itself, and their electronics amplifier circuits. In the Geiger tube, ions produced by penetrating radiation are attracted and move rapidly toward electrodes with a high voltage potential. These ions in motion strike other atoms with sufficient force to knock other electrons out ("inelastic collisions") and create other ions, thus increasing the total amount of ionization within the area. This phonomenon, known as "gas-amplification", produces a literal avalanche of ions for each photon or particle entering the chamber. With farther electronic amplification, each avalanche of ions may be indicated by the deflection of a meter needle and/or an audible "click".

The accuracy of instruments of this type is plus or minus 15%, making them unsuitable for precision measurements, but they are available as small, compact units and provide instantaneous measurement.

Instrument Calibration

Radiographers must be able to determine if the survey meters are operating properly and to check instrument calibration for correct readings (accuracy). Making such a check involves the following:

1) obtain a source of radiation, such as a radioisotope, for which the intensity is known.
2) place the survey meter at a distance computed to give a desired field intensity.
3) read the instrument to determine if the indicated reading is accurate.

This procedure and the required calculations will be discussed in greater detail later in this module under Geometric Principles and Applications.

Radiation Safety

Gamma and X-radiation are the primary radiation sources used in industrial radiography. Both can travel many feet through the air and penetrate deeply through human tissue, causing bioligical changes and damage in cell structure. Radiation safety practices are based on these characteristics and effects of radiation, and are designed to minimize exposure to personnel.

Radiation Dose Measurement

The damaging effects of radiation to living cells are dependent upon both the type and the energy of the radiation to which they are exposed. For this reason, exposure is first measured in physical terms; then, a factor to allow for the relative biological effectiveness of the different types and energies of radiation is applied.

The units used to measure radiation exposure are defined as follows:

- Roentgen: the unit for measuring penetrating external radiation, gamma or X-ray, in air only, which is abbreviated R. It can be subdivided into a smaller unit, the milliroentgen, abbreviated mR, which is 1/1000 of a roentgen.
- Rem: the term used to measure penetrating radiation in animal tissue or man. The rem (roentgen equivalent man) thus defines the biological effect of radiation on man, and is equivalent to the radiation absorbed dose (rad) multiplied by the relative biological effectiveness (rbe) of the radiation absorbed. The rem can be subdivided into the millirem, 1/1000 of a rem, and abbreviated mrem.
- Rad: the unit of measurement of radiation absorbed by humans. The rad (radiation absorbed dose) represents an absorption of 100 ergs of energy per gram of irradiated material, and applies to any type of radiation.
- Quality Factor (QF): the value of assigned to various types of radiation, based on the relative effect on the human body. QF values are shown in Table 26-5-3.

TABLE 26-5-3. Quality Factor (QF) Values

Radiation	QF
X-Ray	1
Gamma	1
Beta Particles	1
Thermal Neutrons	5
Fast Neutrons	10
Alpha Particles	20

In radiography work, gamma and X-radiation are of primary interest. Radiation safety levels are established in terms of rem dose. The calculating of rem dose is simplified by two facts: 1) the Roentgen dose is equivalent to the rad dose, and 2) the QF of both X- and gamma radiation is one. A measurement of Roentgen dose (or radiation intensity, with a survey meter) becomes a measurement of rem dose.

Control of Radiation Exposure of Personnel

Standards for protection against radiation hazards are outlined in the Code of Federal Regulations, Title 10, Part 20. The Code requires that users of radioactive materials "make every reasonable effort to maintain radiation exposure as low as in reasonably achievable," and prohibit individual radiation doses from exceeding the limits specified in Table 26-5-4.

TABLE 26-5-4. Radiation Dose Limits

Type of Exposure	Rems Dose, per calendar quarter
Whole body; head and trunk; active blood-forming organs; lens of eyes; or gonads	1 1/4
Hands and forearms; feet and ankles	18 3/4
Skin of whole body	7 1/2

Under certain conditions, the limit for whole body exposure may be increased to 3 rem in one calendar quarter. These limits are applied to the total amount of radiation received from radioactive materials, and other sources of radiation, such as X-ray equipment.

Protection Against Radiation

Three principles govern safety practices for controlling body exposure to radiation: time, distance and shielding. Safe radiographic installations and techniques are designed by applying these principles.

- Personnel exposure time: The amount of radiation absorbed by the human body is directly proportional to the time the body is exposed. A person standing in a radiation field of 120 mR/hour would receive a dose of 2 mR each minute he remained at that location (e.g. 20 mR in/0 minutes, 40 mR. in 20 minutes, etc.) Work should be organized to spend the least possible time in any radiation field to minimize the dose received. See Figure 26-5-7.

Figure 26-5-7.

- Working Distance: Lower personnel exposures will be received at longer distances from radiation sources. The inverse square law is used to calculate radiation intensities at various distances from a source. The inverse square law is expressed as:

$$\frac{I_1}{I_0} = \frac{D_0^2}{D_1^2}$$ where I_1 and I_0 are radiation intensities at distances D_1 and D_0 respectively.

Table 26-5-5 lists dose rates of commonly used radioisotopes:

TABLE 26-5-5. Radioisotope Dose Rates

RADIOISOTOPE	DOSE RATE, R/HR/CURIE AT 1 FOOT
COBALT-60	14.5
IRIDIUM-192	5.9
CESIUM-137	4.2
THULIUM-170	0/03

The following examples illustrate methods used to calculate radiation intensities in terms of dose rate:

Example 1: Given a 10 Curie Cobalt-60 source, what is the emission or dose rate at 5 feet?

Step 1: From Table 26-5-6, the dose rate of Cobalt-60 is 14.5 R/hr/Ci at 1 foot. The dose rate of a 10 curie source at 1 foot is: 10 x 14.5 = 145 R/hr.

Step 2: I_0 = 145 R/hr

I_1 = ?

D_0 = 1 foot

D_1 = 5 feet

Step 3: Substituting in the inverse square equation,

$$\frac{I_1}{145} = \frac{1^2}{5^2} = \frac{1}{25}$$

Step 4: Solving for I_1 (intensity at 5 ft) -

$$I_1 = 145 \times \frac{1}{25} = \frac{145}{25} = \underline{5.8 \text{ R/hr.}}$$

Example 2: A 20 Curie source of Iridium-192 is used at a distance of 20 feet from a technician. What dose rate will be received?

Step 1: From Table 26-5-6, the dose rate of Iridium-192 is 4.9 R/hr/Ci at one foot. The dose rate of a 20 curie source at one foot is 20 x 5.9 = 118 R/hr.

Step 2: I_0 = 118 R/hr

D_0 = 1 foot

I_1 = ?

D_1 = 20 feet

Step 3: Substituting in the inverse square equation:

$$\frac{I_1}{118} = \frac{1^2}{20^2} = \frac{1}{400}$$

Step 4: Solving for I_1 (intensity at 20 ft) -

$$I_1 = 118 \times \frac{1}{400} = \frac{118}{400} = \underline{0.295 \text{ R/hr}} \text{ or}$$

295 mR/hr

Example 3: In example 2, at what distance from the source should the technician be to receive a dose rate of only 5 mR/hr?

Step 1: Dose rate at one foot, 118 R/hr or 118,000 mR/hr

Step 2: I_0 = 118,000 mR/hr

D_0 = 1 foot

I_1 = 5 mR/hr

D_1 = ?

Step 3: Substituting in the equation:

$$\frac{5}{118,000} = \frac{1^2}{D_1^2}$$

Step 4: Solving for D_1 (distance where intensity is 5 mR/hr):

$$D_1^2 = \frac{1^2}{5} \times 118,000 = \frac{118,000}{5} = 23,600$$

$$D_1 = \sqrt{23,600} = \underline{153.6 \text{ feet}}$$

The same equation is applicable for calculating x-radiation intensities and distances, but it is first necessary to measure the intensity at a known distance from the X-ray source with predetermined ma and kv settings. Any change in X-ray machine settings will change the intensity, and a new intensity measurement would be required.

Personnel should remain as far from the source as possible at all times. See Figure 26-5-9.

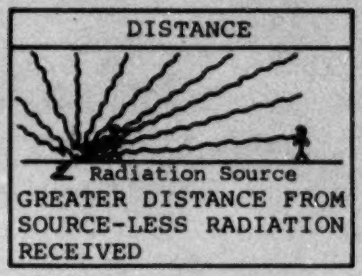


Figure 26-5-8

- Radiation Shielding: Some industrial situations require high intensity sources to be used frequently in confined areas. Having to work in close proximity to such a source, the radiographer may use shielding to minimize exposure to personnel. See Figure 26-5-9.

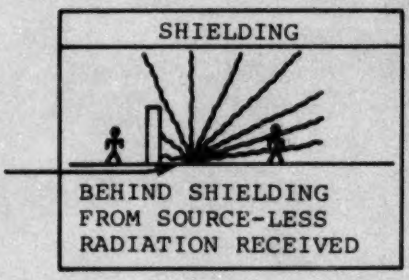


Figure 26-5-9

Gamma and X-rays are not wholly stopped, but are diminished in number by any given absorber. Materials having a high atomic number absorb more radiation than a material having a low atomic number. Lead, iron, concrete and water are commonly used shielding material.

The shielding efficiency of materials is measured in terms of half-value layers. The half-value layer is that amount of shielding which will stop half of the radiation of a given intensity. Tables 26-5-6 and 26-5-7 show the approximate half-value layers of shielding materials for gamma and X-rays respectively.

TABLE 26-5-6. Approximate Gamma Ray Half Value Layers

Shielding Material, In Inches	Half-Value Layer Thickness for Radioisotope Source		
	Cobalt-60	Iridium-192	Cesium-137
Lead	0.49	0.19	0.25
Steel	0.87	0.61	0.68
Concrete or Aluminum	2.6	1.9	2.1

TABLE 26-5-7. Approximate X-Ray Half Value Layers

Shielding Material	Half-Value Layers for X-Ray Tube Potential of:							
	50kV	70kV	100kV	125kV	150kV	200kV	250kV	300kV
Lead (mm)	0.05	0.18	0.24	0.27	0.3	0.5	0.8	1.3
Concrete (in)	0.2	0.5	0.7	0.8	0.9	1.0	1.1	1.2

The following examples illustrate the application of half-value layer information for reducing radiation intensities:

Example 1: In a previous example, a 20 Curie source of Iridium-192 was used at a distance of 20 feet from a technician, where the dose rate was 295 mR/hr. How much lead shielding would be required to reduce the radiation intensity to 10 mR/hr or less?

Step 1: Each half-value layer of lead placed between the technician and the source reduces the dose rate by 1/2. Thus,

1 Half-Value Layer (1/2 x 295 mR/hr) = 148 mR/hr
2 Half-Value Layer (1/2 x 148 mR/hr) = 74 mR/hr
3 Half-Value Layer (1/2 x 74 mR/hr) = 37 mR/hr
4 Half-Value Layer (1/2 x 37 mR/hr) = 19 mR/hr
5 Half-Value Layer (1/2 x 19 mR/hr) = <10 mR/hr

5 Half-Value Layers reduces the radiation intensity to less than 10 mR/hr.

Step 2: From Table 26-5-7, for Iridium-192, each half-value layer of lead is 0.19 in. thick. Five half-value layers of lead shielding are required, or 5 x 0.19 in. = 0.95 in.

Example 2: Radiation from a 300kV X-ray machine in an adjacent area is measured to be 200 times greater than the acceptable safe limit. How thick a concrete wall is required to reduce the radiation intensity to a safe level?

Step 1: Each half-value layer of concrete placed between the X-ray source and the subject area reduces the intensity by 1/2. Thus,

1 HVL = 1/2 original intensity
2 HVL = 1/2 x 1/2 = 1/4 original intensity
3 HVL = 1/2 x 1/4 = 1/8 original intensity
4 HVL = 1/2 x 1/8 = 1/16 original intensity

5 HVL = 1/2 x 1/16 = 1/32 original intensity
6 HVL = 1/2 x 1/32 = 1/64 original intensity
7 HVL = 1/2 x 1/64 = 1/128 original intensity
8 HVL = 1/2 x 1/128 = 1/256 original intensity
8 half-value layers will reduce the dose rate to a safe level.

Step 2: From Table 26-5-8, for X-ray tube voltage of 300-kV, the half-value layer thickness of concrete is 1/2 inches.
8 half-value layers are required, or
8 x 1.2 = 9.6 inches

Geometric Principles

General

A radiograph is a shadow picture of an object placed in a radiation beam. When an object is placed between a radiation source and a piece of film, a shadow of the object will be cast upon the film, producing a radiograph. See Figure 26-5-10. The image on the film must be developed chemically, of course, so that it can be viewed.

The relationships illustrated are caused by X- and gamma rays obeying the laws of light, except that materials are more or less transparent to the radiation. In passing through matter, however, some of the rays are absorbed. The amount of absorption at any point is dependent upon the thickness and density of the matter at that point, and procedures variation in the intensity of the emerging rays. This variation is detected and recorded on the radiographic film.

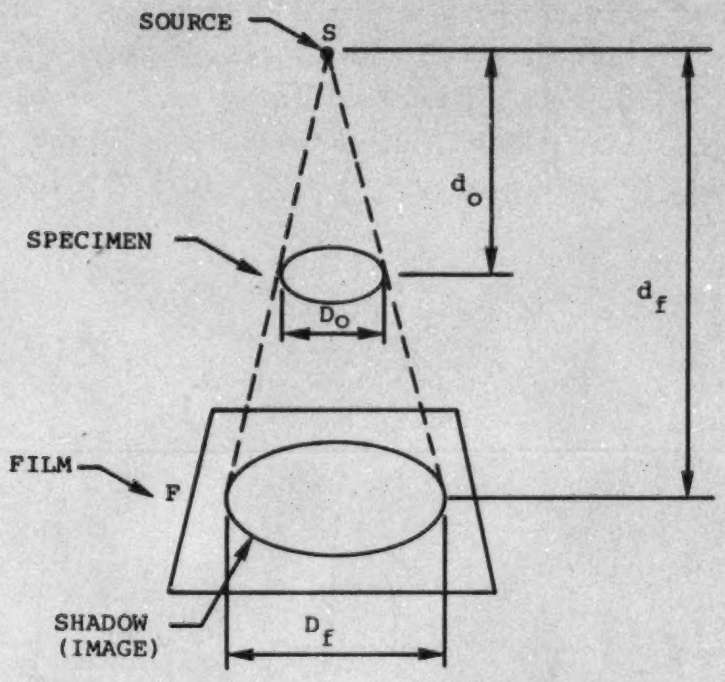


Figure 26-5-10. Shadow Formation

As illustrated in Figure 26-5-10, the enlargement of the image is caused by the film not being in contact with the specimen. If the object were lying on the film, there would be little or no enlargement. The ratio of the diameter of the object (D_o) to the diameter of the shadow (D_f) is equal to the ratio of the distance from the source to the object (d_o) to the distance from the source to the film (d_f), i.e., $\frac{D_o}{D_f} = \frac{d_o}{d_f}$.

Film Image Sharpness

Optimum geometrical sharpness of the image is obtained when the radiation source is small, the distance from the source to specimen is relatively large, and the distance from the object to the film is small. The geometrical unsharpness, or "penumbra", is illustrated in Figure 26-5-11.

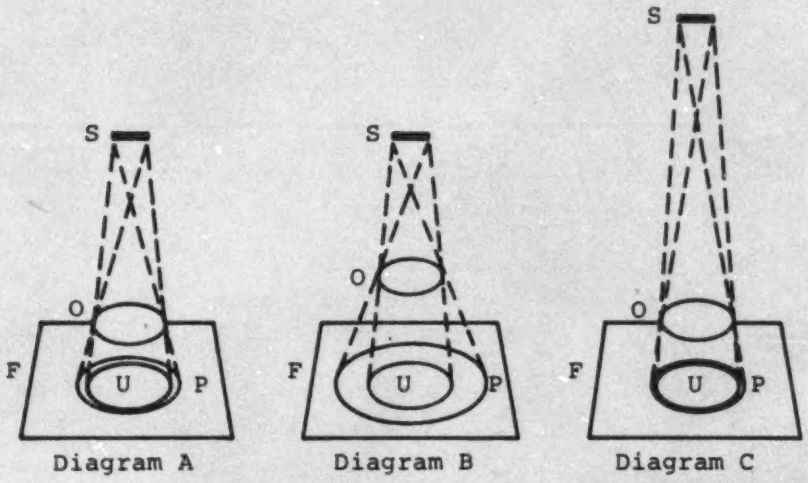


Figure 26-5-11. Geometrical Unsharpness, Penumbral Shadow

Legend:

S - Source
O - Object
F - Film
U - Umbra
P - Penumbra

Diagram A shows a small geometrical unsharpness (penumbra) when the specimen is close to the film.

Diagram B shows a greater geometrical unsharpness as the object is moved further from the film.

Diagram C, with the object-to-film distance the same as diagram A, shows the decrease in unsharpness as the source is moved further away from the object, increasing the source to film distance.

Film Image Distortion

Object images on film may be distorted as a result of:

- the plane of the specimen and the plane of the film are not parallel, and/or
- the radiation beam is not directed perpendicular to the plane of the film.

The resulting image distortions of the specimen also apply to the images of included discontinuities; this must be considered to avoid incorrect interpretation of the radiograph.

Film Image Enlargement

If the specimen is not in contact with the film some enlargement will take place, enlarging also any included discontinuities. In thick specimens, the images of discontinuities located away from the film side of the object will also be enlarged. Enlargement can cause misjudgement about the size of defects, but may also reveal small defects not noticeable on regular radiographs.

Summary

To produce an accurate representation of the specimen on the radiograph with a minimum of unsharpness, and distortion the following criteria should be observed:

- the radiation source should be as small as possible.
- the distance from the source to the film should be as large as practical.
- the film should be in contact with or as close to the specimen as possible.
- the center ray of the radiation beam should be perpendicular to the film
- the plane of maximum interest on the specimen should be parallel to the film.

Radiographic Film

Radiographic film consists of a thin, transparent plastic sheet coated on one or both sides with a radiation-sensitive emulsion of gelatin and silver bromide crystals. The silver bromide crystals react when exposed to X-, gamma or visible light radiation, are reduced to black metallic silver in the chemical developing process, and produce a dark gray image on the film. The film is viewed by using a bright light source (film viewer) and observing the image represented by high density (dark) areas and low density (light) areas.

The acceptability or usefulness of the resulting radiograph (e.g., whether the images of the specimen and discontinuities are identifiable) is dependent on adequate contrast and definition. Contrast is a comparison, or the difference in light transmission, between the high density areas and the low density areas, and definition if the relative sharpness of the image.

Radiographic Contrast

Radiographic contrast is a comparison of densitites on developed film, resulting from the following variables:

- Radiation source intensity (X-ray kilovoltage or gamma ray energy)
- Subject contrast

- Film density
- Screen usage
- Radiation scatter

These variables produce the effects listed:

- Radiation source intensity: generally, contrast is increased by lowering X-ray kilovoltage or by lowering the gamma ray MeV (e.g., substituting Ir-192 for Co-60 sources).
- Subject contrast: absorption of the radiation by the specimen is proportional to the thickness at any point (i.e., film exposure is greater at thinner areas of the specimen)
- Film characteristics: films are manufactured to produce different film contrasts and other properties.
- Film density or darkness is determined by exposure (radiation intensity X time), where increased exposure produces increased darkening, and by chemical processing, where increased development time produces increase darkening. Generally, film contrast increases as film density increases.
- Screen Usage: contrast may be increased with the use of fluorescent screens, which intensify the image, and with lead screens, which reduce back-scattered radiation and intensify the image.
- Radiation scatter: film fogging and loss of contrast may result from scattered radiation produced by rays deflected by the specimen, the film holder, the film, or the walls and floor.

Film Contrast and Denstiy, H & D Curve

Radiographic sensitivity is dependent upon the film contrast characteristics, or the ability of the film to detect and record different radiation exposures as differences

in density. The relationship of film density to radiation exposure is described by the H & D curve, or characteristic curve for any particular film.

Exposure, E, of a film is defined as the product of the radiation intensity, I, reaching the film and the radiation exposure time, t.

$$E = I \times t$$

Since there are no convenient units, suitable to all X- and gamma radiation conditions, in which to express radiographic exposures, a relative exposure is used as one axis in plotting the H & D curve. Any exposure given a film is expressed in terms of any other exposure, producing a relative scale. For convenience, the logarithm, to the base 10, of the relative exposure itself is used, producing a compressed scale.

Film density, or more correctly called optical density, is plotted along the other axis on a linear scale and is defined mathematically as:

$$D = \log_{10} \frac{I_o}{I}$$

where: D = film density

I_o = intensity of light incident upon the film (or behind)

I = intensity of light transmitted through the film

The following example illustrates these concepts and the usefulness of the H & D curve:

1) A specimen with a thick section, A, and a thinner section, B, is radiographed: See Figure 26-5-12.

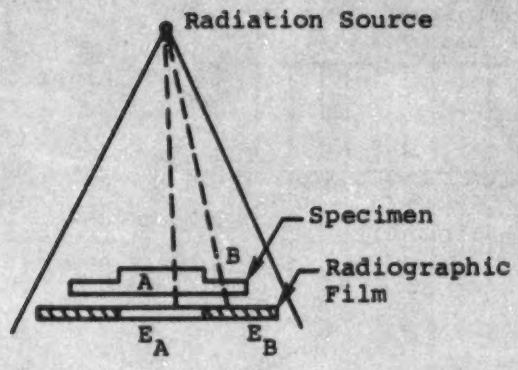


Figure 26-5-12. Producing the Radiograph

2) The exposed film, when developed, will have <u>contrast</u> between the area of low density, E_A, and the area of high density, E_B, See Figure 26-5-12.
3) When the developed radiograph is viewed on an illuminator, light will be transmitted in varying amounts through the film, as a result of the density differences, or <u>contrast</u>. See Figure 26-5-13:
4) The eye can readily interpret large density differences, or contrast, but there is a lower limit of contrast that cannot be detected by the naked eye. As the exposure and overall film density increases, the contrast increases; the H & D curve has a contour reflecting this relationship. (See Figure 26-5-14.

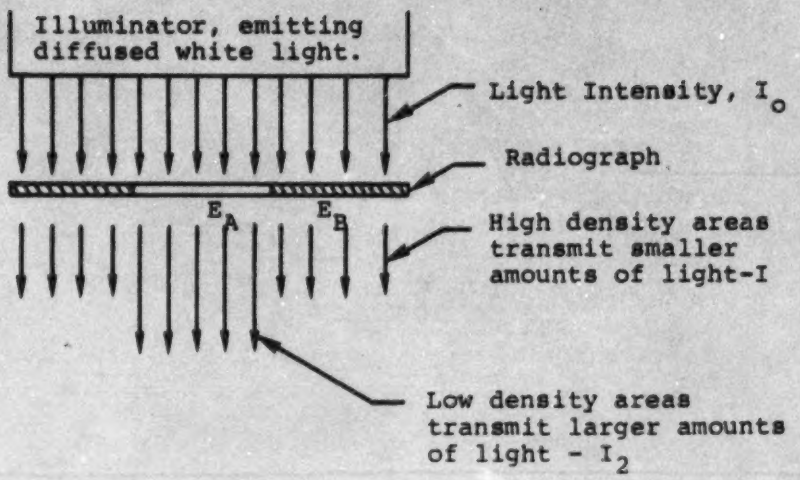

Illuminator, emitting diffused white light.
Light Intensity, I_o
Radiograph
E_A
E_B
High density areas transmit smaller amounts of light-I
Low density areas transmit larger amounts of light - I_2

Figure 26-5-13. Film Density

In the case of the radiograph illustrated in Figures 26-5-12 and 26-5-13, it can be seen that the film exposure E_A at radiation path A is less than the exposure E_B at radiation path B. For a low exposure at E_1, the result is that film density dA_1 is less than film density dB_1. The difference in denstiy, $dD_1 = dB_1 - dA_1$, is <u>film contrast</u>. In the low density portion of the H & D curve, i.e., density less than 1.0, the low contrast dD_1 will probably not be discernible by the eye.

By increasing the exposure to the value represented by E_2, the overall density of the radiograph is increased and the <u>contrast</u> or density difference between E_A and E_B (i.e., dA_2 and dB_2) is greatly increased. The resulting contrast is easily detectable by the eye. In this manner, the film's contrast characteristics may be used to select the exposure which will amplify the subject contrast. It may be stated that curve is a measure of film contrast.

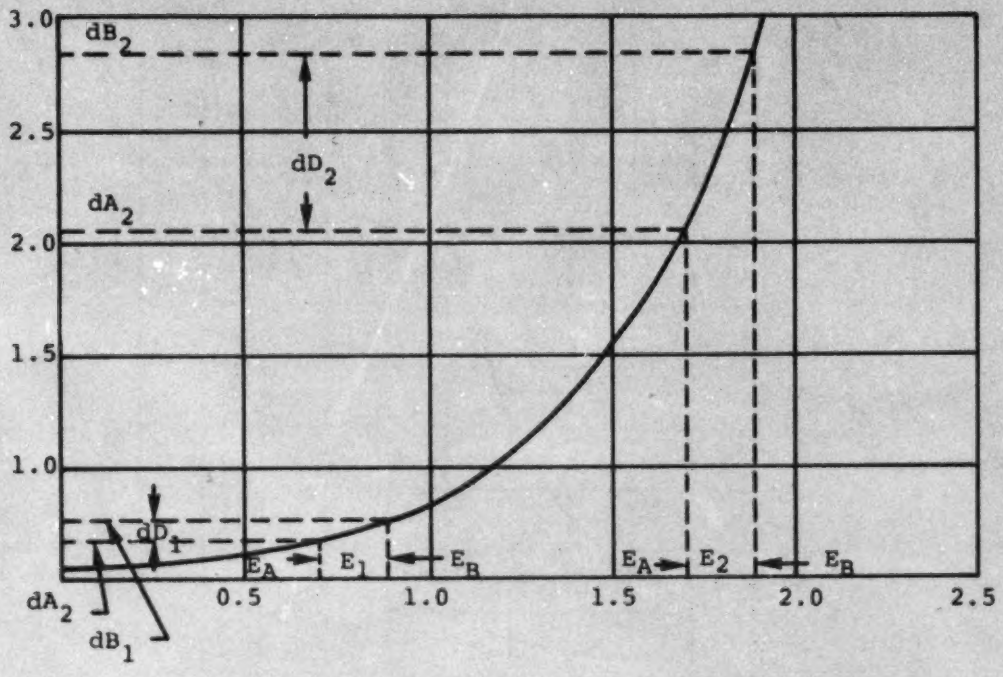


Figure 26-5-14. Film Characteristic Curve, "H & D" Curve

The H & D curves for films are also influenced by the film speed or film sensitivity. Film speed is the relative exposure required to obtain a desired film density. Generally, a high-speed (fast) film requires a low exposure, while a slow-speed film requires more exposure to reach the same density.

Film speed of films, Figure 26-5-15, is indicated by the position of H & D curves along the log E axis. Faster films are located toward the left, and slower ones to the right.

In industrial radiography, films should be exposed to produce maximum radiographic contrast. It can be seen from the H & D curves shown in Figure 26-5-15, that the slopes

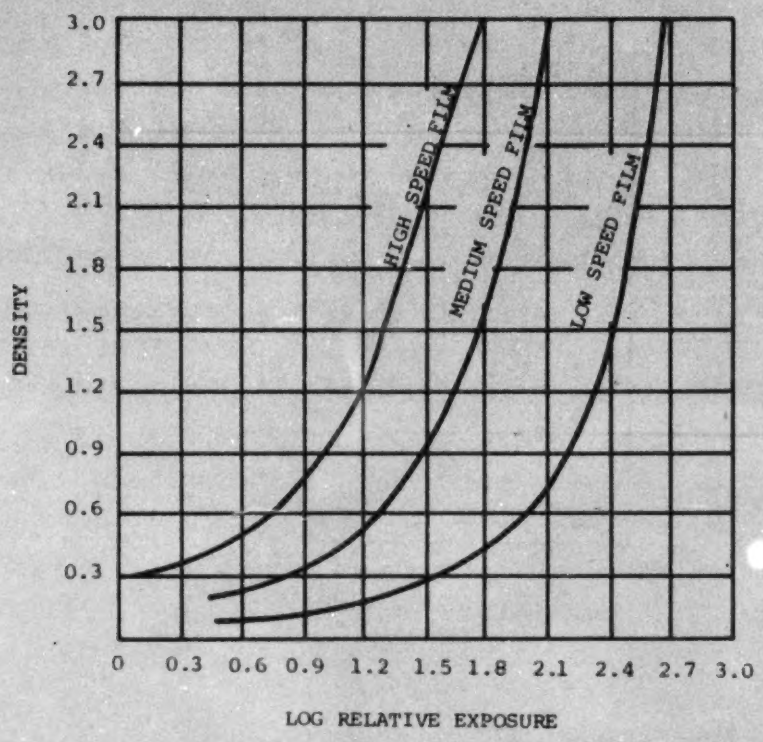


Figure 26-5-15. Relative Film Speed

of the curves are the steepest above a density of 1.5, and in most areas, film should be exposed to obtain a minimum density of 1.5, thereby optimizing film contrast characteristics.

If is known that the density of a film increases with increasing exposure up to a maximum value. Increasing the exposure beyond this point results in an actual decrease of density. This phenomenon is referred to as reversal.

Film Graininess

Graininess is the grouping or clumping of minute silver particles that form the image or radiographic film. This characteristic determines the fineness of detail that can be perceived on a film. Generally, fast films have large grain and poor resolution characteristics, while slow films have fine grain and good resolution.

Film Selection

The radiograph must have acceptable quality to resolve the specimen discontinuities which are likely to affect the specimen in service. Film contrast, speed, and graininess are interrelated, so the proper film must be specified to provide the desired contrast, image sharpness, and minimum exposure time. Films of various characteristics are available for many specific purposes and may be selected to meet these criteria.

Film Processing

Once a radiographic exposure has been made, the film must be processed chemically to convert the latest image into a visible one. The process includes five distinct steps, Developing, Stop Bath, Fixation, Washing, and Drying, which are described as follows:

- Developing: The chemical reaction involved in reducing the silver bromide crystals in the film emulsion to metallic silver.

  Commercially prepared developers are usually used, which are obtained in powder or liquid form and dissolved in or diluted with water.

  The developing process begins when the film is put into the developer solution. The amount of silver bromide changed is a function of time and the

chemical solution strength and temperature. The density of the radiographic image is proportional to the length of time the film remains in the solution up to a limit, beyond which chemical fogging may occur with a decrease in contrast. Normal developing time for industrial radiographic films is usually 5 to 8 minutes to obtain optimum density and contrast.

The developing process is also temperature-sensitive. Normally, solution temperatures are maintained at 68°F (20°C). Lower temperatures will retard the action of the chemicals sufficiently to produce underdevelopment, and excessively high temperatures can fog the film or soften and damage the emulsion.

In addition to time and temperature control, agitation of the film in the developer is necessary for development uniformity. Shaking the film holders for a few seconds every minute of development time usually produces satisfactory results.

Replenishment or replacement of the developer solution is also required as the solution becomes weaker through use. Exhaustion of the developing agent occurs as silver bromide is converted to metallic silver, and the reaction products accumulate in the solution. If replenisher is used, the developer should be discarded when the quantity of the replenisher added equals 2 to 3 times the original quantity of the developer.

- Stop Bath: A mild acetic acid solution used to arrest film development.

The stop bath solution is used to remove the residual developer from the film, stop the development

action, and prevent uneven development and film streaking. It also serves to neutralize the alkali retained in the emulsion, permitting the acid in the fixer solution to function effectively. The proper stopping procedure is to:

1) remove film from the developer and allow to drain for a few seconds
2) immerse film in stop bath for 30-60 seconds with moderate agitation
3) remove film for transfer to the fixer solution

The stop bath solution should be maintained at the same temperature as the developer, and replaced when exhausted. When fresh, the solution is yellow in color; when spent, the color changes to a blue-purple.

- Fixation: The use of an acidic solution which removes the unexposed silver bromide crystals remaining in the fiber emulsion.

If not removed, the remaining crystals will darken when exposed to light and ruin the radiograph.

The fixer solution also hardens the gelatin on the film so that it will withstand drying with warm air.

Films should be agitated vigorously when placed in the fixer, then at two minute intervals. Fixing time should be approximately twice the time it takes to clear the undeveloped silver halide from the film (clearing time), or from about 8 to 15 minutes, depending on the solution age or usage.

The temperature of the bath should be maintained between 65°F and 70°F. To maintain the solution activity, replenisher may be added twice, in accordance with the manufacturer's instruction, before the solution is discarded and replaced.

- Washing: The thorough flushing of developed and fixed film to remove the residual fixer.

  Films should be rinsed in running water of 65°F to 70°F temperature for 20 to 30 minutes, making sure that the entire emulsion area is exposed to frequent water changes or an hourly flow rate of 4 to 8 times the tank volume.

  When film is removed from the wash tank, small drops of water cling to the emulsion, which can cause spotting and streaking on the finished film. The film may be immersed in a wetting agent solution for one or two minutes to cause the water to drain off more evenly and prevent or reduce such damage.

- Drying: The final step of film processing, usually accomplished by hanging the film in a drying cabinet, or in an area where dry air circulates freely to uniformly dry both sides of the film simultaneously.

The entire film processing cycle is shown in Figure 26-5-16.

Film Processing Facilities

All radiography operations must have film processing facilities; either automatic processing or manual processing equipment may be used.

An automatic processing machine is a complete integrated system which accomplishes all required processing steps from development through rinsing and drying. The only manual operations necessary are the loading and unloading of the film. The entire processing cycle is completed in less than 15 minutes through the use of special chemicals, continual agitation of the film, elevated chemical temperatures, and

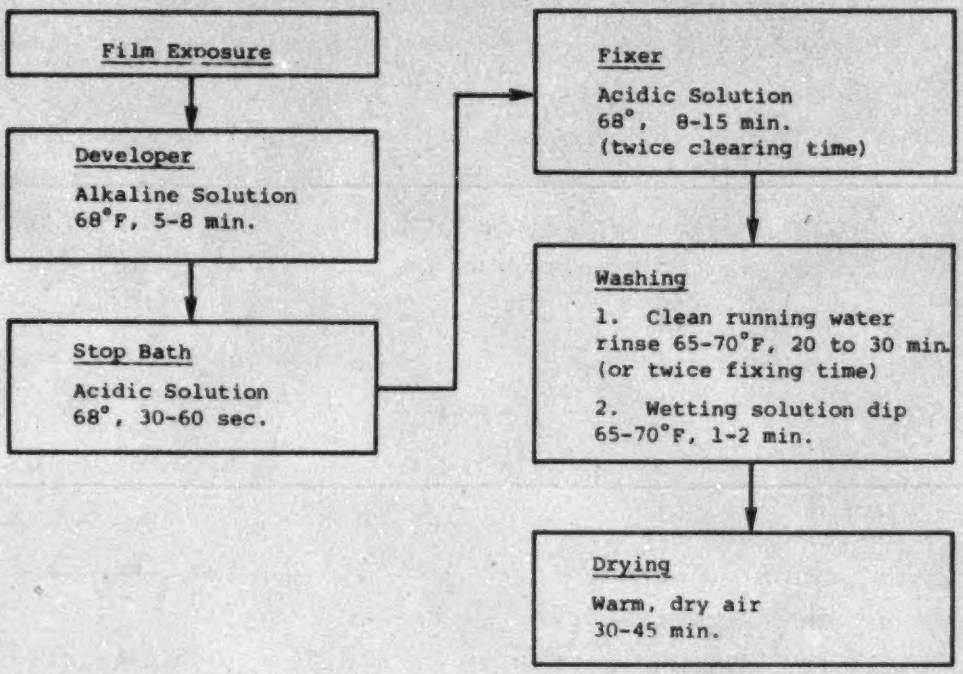


Figure 26-5-16. Film Processing Cycle

drying with jets of heated air. Automatic processors, when properly operated and maintained, consistently produce radiographs of higher quality than those processed manually.

Manual film processing operations must be performed in a darkroom under appropriate safelight conditions. The location, design and construction of the facility depends on the volume of processing work to be done. The basic equipment components needed are: loading bench for handling film, film storage cabinets, chemical processing tanks and film dryer. For high quality results in manual film processing, the following factors must be implemented:

- darkroom areas shall be lighted with safelights of sufficient intensity for processing operations without endangering film by exposure to light.
- darkroom must be protected against light from outside sources.
- "wet" and "dry" areas must be separated to preclude film damage from water and chemicals.
- a high degree of cleanliness must be maintained in all areas to prevent contamination from dust, dirt and chemicals.

Radiographic Accessory Equipment

Screens

Radiographic screens are used to intensity the photographic action of radiation on the film, and to improve the image by absorbing scattered radiation.

Lead foil screens, usually from 0.004 to 0.006 inches thick, are normally used on both sides of the film in industrial radiography to improve the radiographic quality. The intensifying action of the lead foil screen is caused by the electrons emitted under gamma or X-ray excitation. Lead screens are used for almost all exposures when using high-voltage radiography.

Fluorescent screens have the ability to absorb gamma and X-rays and emit light (fluoresce). Film may be clamped between a pair of these screens during exposure, thereby intensifying the image. This technique may produce excessive graininess, however, and is seldom used in high-energy industrial radiography.

Filters

Filters are generally used in X-ray radiography, between the radiation source and the specimen, to absorb scattered radiation. Filters are usually made from metals with a high atomic number, such as lead, steel or copper, and absorb more of the "soft" or low intensity X-rays than the "hard" or high intensity X-rays. They are useful in minimizing over-exposure of thin areas of the specimen, and reducing undercut near the edges of the specimen. Experience has shown that in the radiography of steel specimens, a lead filter of about 3% or a copper filter of about 20% of the maximum steel thickness gives good results.

Masks and Shields

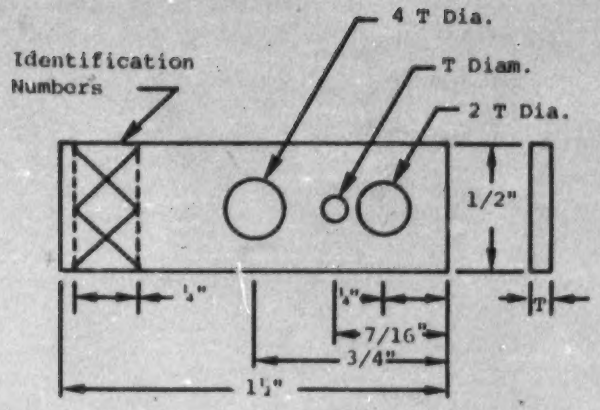
Radiation scatter reaching the film may also be minimized with the effective use of masks and shields of lead, barium clay, metallic shot or other absorbent material placed around portions of the specimen or areas surrounding the specimen. Masks absorb the soft rays and many of the higher energy rays, and shields limit scatter by absorbing rays that strike walls, floors and other objects that would generate scattered radiation.

Penetrameters

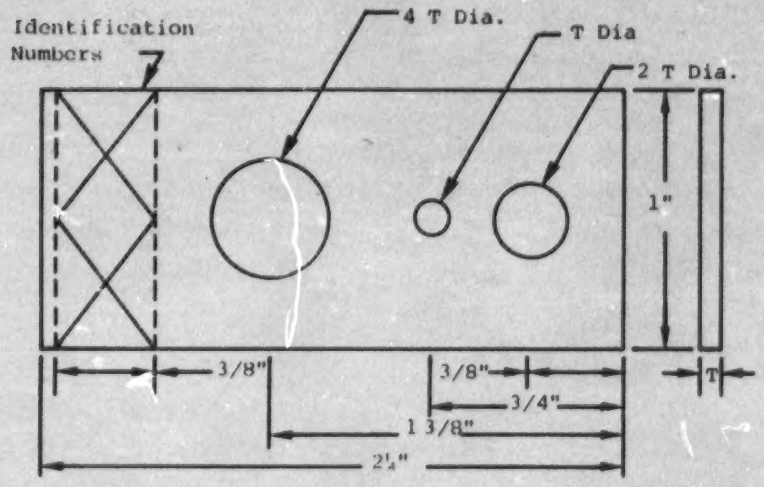
A penetrameter is a device whose image on a radiograph indicates the quality and sensitivty of the radiograph. The standard penetrameter is a small rectangular strip of material, radiographically similar to the material being radiographed, with 2 drilled holes of set diameter. The penetrameter is identified by a lead number (ID No.) which indicates the maximum thickness of the material for which the penetrameter is normally used.

The thickness of the penetrameter is determined by the required sensitivity of the radiograph. Percent sensitivity is the smallest detectable thickness of the material being examined, expressed as a percentage. The value of 2 percent has been arbitrarily set and is generally accepted for most routine radiographic work. When a penetrameter with a thickness of 2 percent of the specimen thickness is selected for use, therefore, the radiographic sensitivity is said to be 2 percent.

If the construction of nuclear power plants, welding work is conducted in accordance with the requirements of the ASME (American Society of Mechanical Engineers) Boiler and Pressure Vessel Code. Included in this Code are requirements for the radiographic examination of welds, and descriptions of the penetrameters to be used as a check on the radiographic technique. The ASME Code requires a radiographic sensitivity of 2 percent, and a penetrameter thickness of not more than two percent of the thickness of the specimen. The ASTM (American Society for Testing and Materials) type penetrameter, as shown in Figure 26-5-17, is used for ASME work applications, and has provisions for different quality levels of inspection. Each penetrameter contains three (3) drilled holes having diameters of 4, 1 and 2 times the penetrameter thickness (T), with minimum holes sizes of 0.040", 0.010" and 0.020" respectively. The quality levels are established for the penetrameters based on the visibility of the holes on the radiograph. For example, a quality level may be designated as "2-2T", where the first digit indicates a penetrameter thickness of 2% of the specimen thickness, and the "-2T" indicates the hole which must be visible on the radiograph. The Quality Level data is listed in Table 26-5-8.



Penetrameter Design for Thickness from 0.005" to 0.050"
From 0.005" through 0.020" Made in 0.0025" Increments.
From 0.025" through 0.050" Made in 0.005" Increments.



Penetrameter Design for Thickness from 0.060" to 0.160"
Made in 0.010" Increments

Figure 26-5-17. ASTM Penetrameters

Designated Quality Level of Inspection	Penetrameter Thickness	Perceptible Hole Dia.	Equivalent Penetrameter Sensitivity
1-1T	1% of Specimen	1T	0.7%
1-2T	1% of Specimen	2T	1.0%
2-1T	2% of Specimen	1T	1.4%
2-2T	2% of Specimen	2T	2.0%
2-4T	2% of Specimen	4T	2.8%
4-4T	4% of Specimen	4T	4.0%

Table 26-5-8. Quality Levels of Inspection

Film Identification and Orientation

Appropriate marking on the specimen and the radiograph must be provided to permit correct radiographic interpretation. Lead numbers and letters are usually placed on or adjacent to the specimen, during the exposure, attached with masking tape, and appear on the finished radiograph. The specimen is then marked in identical fashion with a pen or scriber to preclude improper identification or orientation.

Applicability of Radiographic Techniques

Radiography is very useful in examining a variety of products, ranging from welding and metal castings, to non-metallic materials such as plastics and ceramics. Regardless of the type of material to be examined, the same basic principles of film density and contrast apply, which are controlled by source-to-film distance, source orientation, source energy, exposure and film type.

For optimum radiographic results, the following factors must be considered for the test arrangement:

- producing best radiographic contrast of that area of the specimen most likely to contain discontinuities
- minimizing exposure time.
- minimizing distortion of the specimen in the area of interest.
- minimizing the number of exposures and films required.

The following sketches illustrate various applications of exposure arrangements:

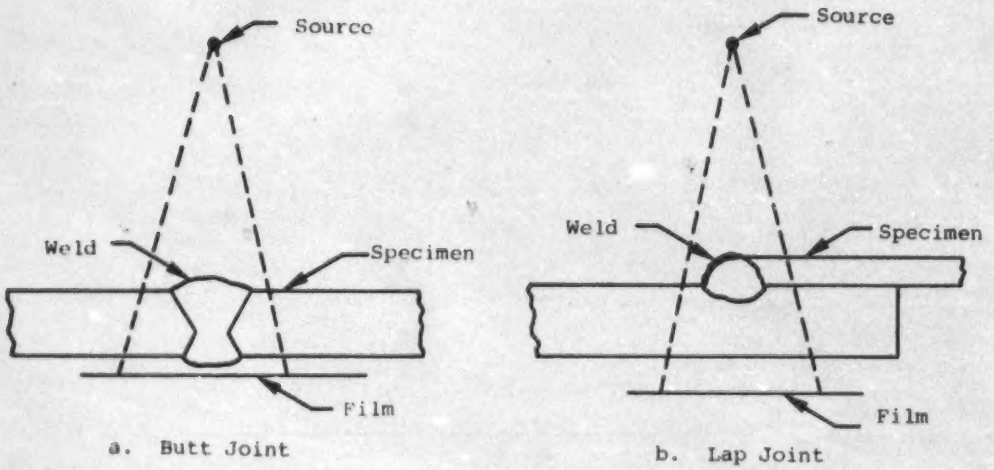
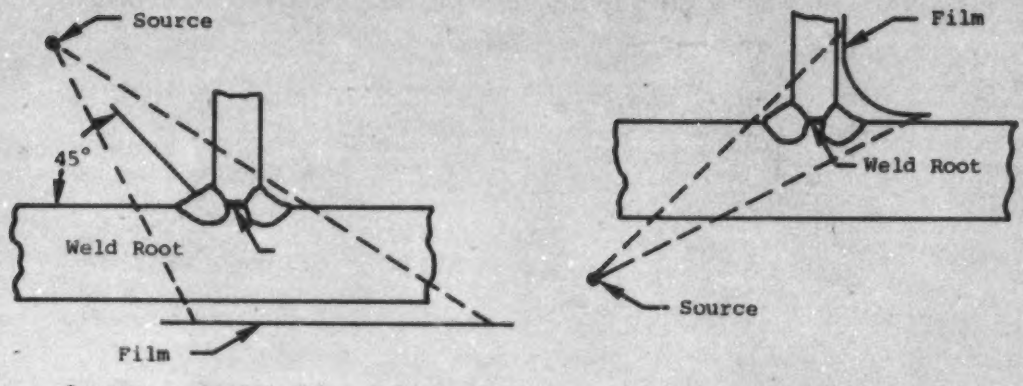


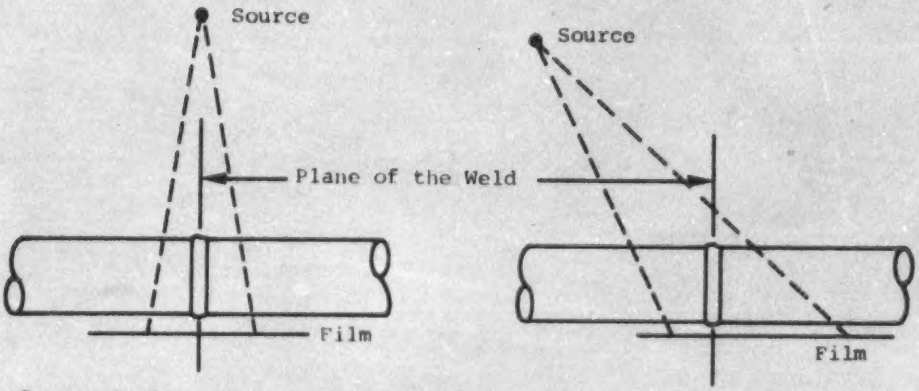
Figure 26-5-18. Flat Welded Plates



a. Source on Welded Side of Base Plate

b. Source on Opposite Side of Base Plate from Welds

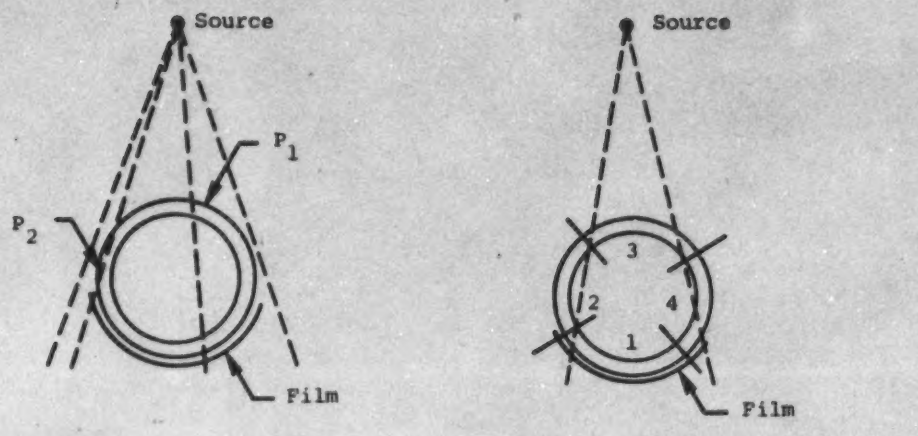
Figure 26-5-19. Welded "T" Joints on Plate



a. Source In-line with Circumferential Weld Axis

b. Source Off-set from Circumferential Weld Axis

Figure 26-5-20. Small Pipe Welds



a. Specimen Variable Density

b. Specimen Multiple Exposures

Figure 26-2-21. Large Pipe Welds

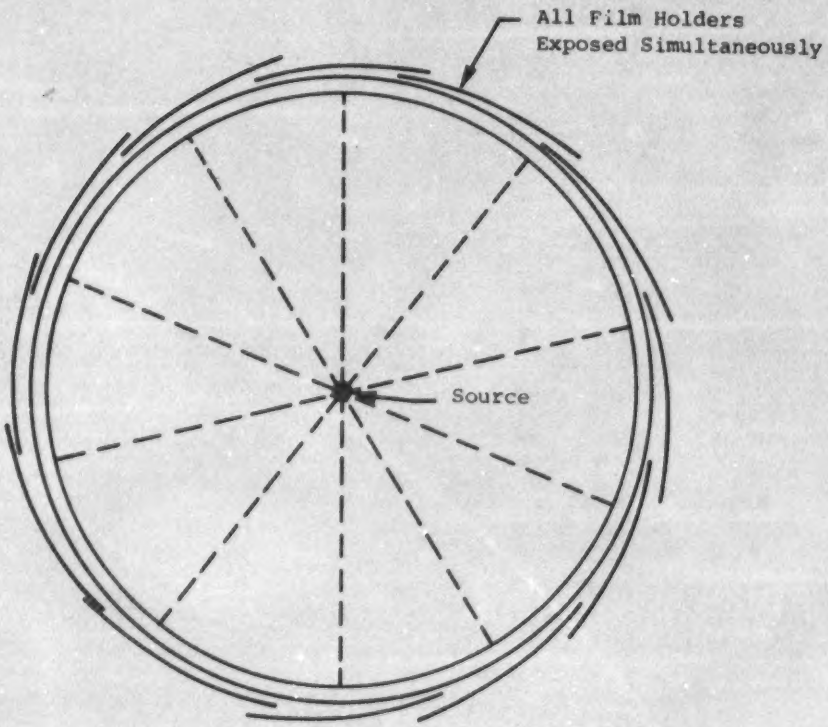


Figure 26-5-22. Panoramic Exposure, Large Pipe or Pressure Vessel

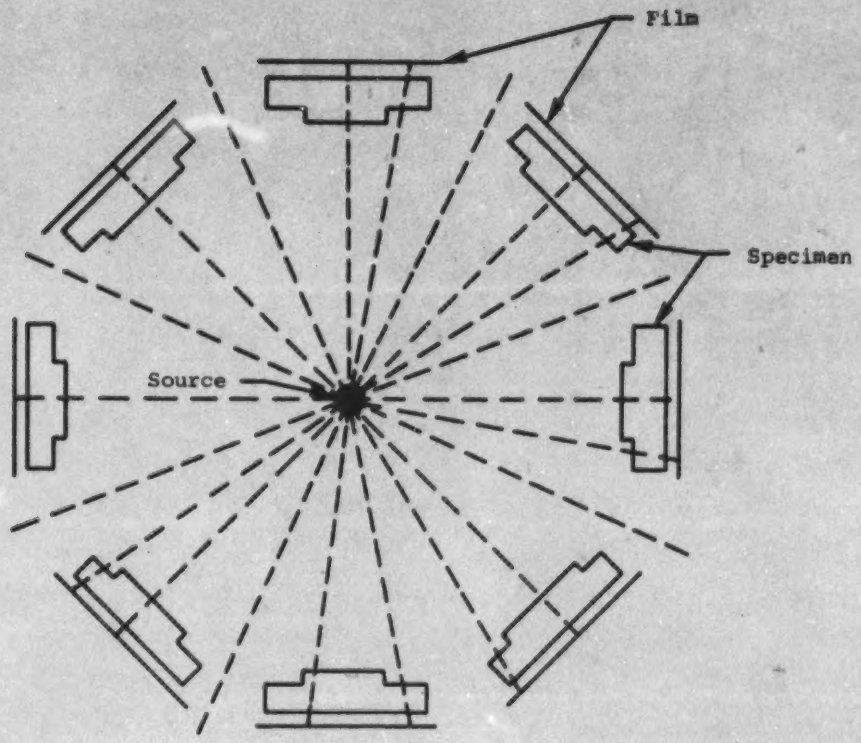


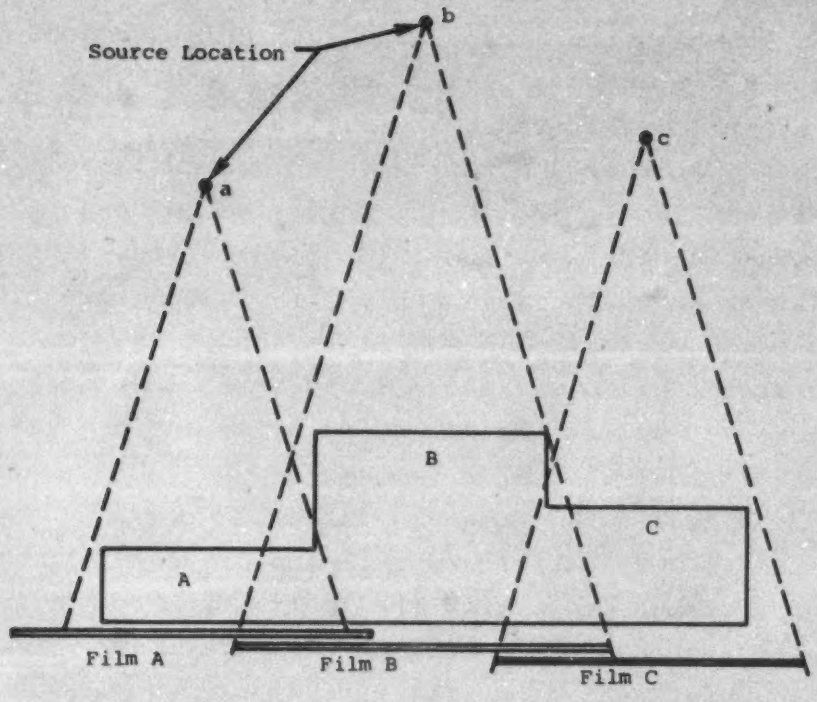
Figure 26-5-23. Panoramic Exposure, Multi-Specimen

Advantages and Disadvantages of Radiographic Techniques

The radiographer must consider and evaluate all factors, including the advantages and disadvantages of appropriate techniques, in selecting optimum test arrangements. The techniques previously illustrated are typical of those used in industrial radiography, and are discussed as follows:

- Figure 26-5-18, Flat Welded Plates

  One of the simplest subjects to radiograph is the welded butt joint. Subject contrast is minimal, the critical area is well defined.



(Specimen with Wide Range of Subject Contrast)

Figure 26-5-24. Multiple Exposure

The lap joint is also a simple arrangement, but the exposure must be made to produce the proper film density on the thicker part of the specimen.

- Figure 26-5-19, Welded "T" Joints or Plate

In the welded "T" joints, discontinuities are generally found in the weld root area. No location can be found, however, for placing the film to obtain good image resolution. Distortion may be minimized by using a long source-to-film distance, but at the expense of greatly increased exposure time.

- Figure 26-5-20, Small Pipe Welds

In radiographing welds on small pipe (1 1/2" or less), the entire weld can be shown on one film. As shown in the first illustration (a), however, it would not be possible to determine whether a defect were present in the near wall or the far wall (relative to the source) due to the superimposed image. The offset arrangement (b) is preferred, because the weld image is cast upon the film as an ellipse, showing all areas of the weld and any included discontinuities. Defects occurring in the wall nearest the source will not be in sharp focus and have clear definition, however, unless the source-to-film distance is large.

- Figure 26-5-21, Large Pipe Welds

The length of the radiation path through large pipe is difficult to measure and presents a problem of variable density in the specimen, which prohibits shooting the entire weld on one film. (The total length of radiation path P_1 in the pipe material is much shorter than the length at path P_2, as shown in sketch a.) It is preferred to divide the circumferential weld into 3 or 4 segments and radiograph each with a separate exposure, as indicated in sketch b.

- Figure 26-5-22, Panoramic Exposure, Large Pipe or Pressure Vessel

If the pipe is large enough, generally 12" or greater in diameter, and its interior is accessible, entire circumferential welds may be radiographed with one exposure, with the film placed on the exterior of the pipe as shown in Figure 8.5. Pressure vessels may be radiographed in the same manner. This technique produces quality radiographs of uniform density in a fraction of the time required to make separate exposures of each area or segment.

- Figure 26-5-23, Panoramic Exposure, Multi-Specimen

  This figure illustrates a technique for radiographing a number of similar specimens, in similar position, with one exposure of the source placed at the geometric center of the arrangement. Much of the set-up time and exposure time required for individual exposures is saved as well as minimizing the radiation exposure hazard to the radiographs.

- Figure 26-5-24, Multiple Exposure

  Specimens with a wide range of subject contrast cannot be radiographed with one exposure, and achieve acceptable radiographic density in all areas. Separate source locations and exposures may be required as shown in this figure. In examining area A of the specimen, for example, Film A would be placed, and the source located at "a". The exposure would be made, Film A removed, and a similar set-up made to examine area B, with the procedure then repeated for area C. This technique provides high resolution of discontinuities throughout the specimen, at the expense of the additional time required for the set-ups and exposures.

EXERCISES

The following exercises serve to reinforce the concepts presented in this module.

1. Define or briefly explain the following terms:
   (a) particulate and electromagnetic radiation
   (b) gamma radiation sources
   (c) X-ray sources

(d) radioisotope source and capsule characteristics
(e) radioisotope cameras and accessories
(f) X-ray machine characteristics
(g) radiation detection and measurement equipment
(h) equipment calibration

2. Explain the principles of radiation safety as related to time, distance, and shielding, and define the following terms: Roentgen, rem, and rad.

3. Given a 4 Curie Cobalt-60 source, calculate the gamma-ray dose rate at:
(a) four (4) feet
(b) eight (8) feet

4. A 20 Curie source of Iridium-192 is used at a distance of 20 feet from a technician where the dose rate is measured at 295 mR/hr. Calculate the amount of lead shielding required if the technician is to work 8 feet from the source and to be in a radiation field of less than 10 mR/hr.

5. Given information such as radioisotope or X-ray dose rate and shielding values, calculate:
- emission or dose rate at a given distance
- dose rates at different distances
- half-value layers of shielding required to meet radiation intensity requirements at specific distances

6. Explain geometrical unsharpness as related to the location of the source specimen and film.

7. Define or briefly explain the following terms:
   (a) film contrast
   (b) subject contrast
   (c) film density
   (d) H & D curve
   (e) film speed
   (f) film graininess

8. Demonstrate a knowledge of the operation and usage of radiation detection and measurement equipment by pointing out and identifying on illustrations or actual devices the various controls, and explaining the method of operation and usage in actual practice. This should be carried out following Procedure #1 given in this module.

9. Demonstrate a knowledge of the operation and usage of x-ray equipment and photographic emulsions employed in radiography as outlined in Procedure #2 given in this module.

10. Visit a welding shop in your area employing radiographic testing of the completed welds. Using Procedure #3 study selected specimens that are to be radiographed and follow the procedure to ensure that the radiographic non-destructive examination test has been set up properly.

MATERIALS

These materials are suggested in reference to carrying out Exercises #8, #9, and #10 of this module. These should be available at the site(s) visited.

1. For Exercise #8 - Laboratory visit where radiation detection equipment is employed.
   a. Pocket Dosimeter
   b. Film Badge
   c. Thermoluminescent Dosimeter (TLD)
   d. Ionization Chamber
   e. Geiger-Mueller Detector

2. For Exercise #9 - Dental x-ray laboratory visit.
   a. Geiger-Mueller Detector
   b. Ionization Chamber
   c. Film badge or TLD
   d. Photographic emulsions to produce radiographics
   e. Photographic developing equipment

3. For Exercise #10 - Welding shop visit to observe radiographic testing.
   a. Specimens to be radiographed
   b. Geiger-Mueller Detector
   c. RT test procedure
   d. Radioisotope or x-ray source
   d. Radioisotope camera and accessories
   f. Photographic emulsions for RT examination
   g. Photographic development equipment

PROCEDURES

The following procedures relate to Exercises #8, #9, and #10 of this module.

1. Procedure #1 - (In reference to Exercise #8)
   a. Visit a laboratory in your area which uses radiation detection and measurement equipment. These would typically be:
      (1) Hospitals employing nuclear medicine
      (2) Nuclear power station
      (3) Radioisotopes laboratory
      (4) Government research reactor facility

   b. Examine the following types of detectors:
      (1) Pocket dosimeter
      (2) Film badge
      (3) Thermoluminescent dosimeter (TLD)
      (4) Geiger-Mueller Detector
      (5) Ionization chamber

   c. Use the ionization chamber and the Geiger-Mueller detector to make radiation survey measurements using either an x-ray or gamma-ray source.

   d. Prepare a report on your visit which includes the data requested in Table 26-5-9 in the Data Table section of this module.

2. Procedure #2 - (In reference to Exercise #9)
   a. Visit a dental office in your area which uses x-ray equipment.

   b. Discuss the operation of this equipment with the laboratory technician.

c. Examine the operating procedures for the use of the x-ray machine.

d. Examine any "fail-safe" safety or warning devices incorporated into its design.

e. Examine the x-ray tube (or source) housing and its construction.

f. Examine the generator cabinet for the x-ray machine and any protective or warning devices associated with the cabinet.

g. With the assistance of the technician, take an x-ray radiograph and measure surrounding radiation loads if possible.

h. Describe the radiographic film developing process. Outline the steps involved, and state approximate dwell times for each step. (Assist in the development of the film, if possible.)

i. Describe methods of reducing scatter.

j. Demonstrate an understanding of personnel safety and radiation protection by reviewing a sketch and description of a typical radiographic test set-up, and list the following:
   (1) Recommended dosimetry
   (2) Personnel precautions
   (3) Calculated permissible "stay times" in radiation areas identified
   (4) Effect of shielding usage specified

k. Collect the data specified on Table 26-5-10 in the Data Table section of this module.

3. Procedure #3 - (In reference to Exercise #10)

a. Visit a welding shop in your area employing the use of radiographic testing of the completed welds.

b. Study the selected specimens to be radiographed.

c. Follow the procedure along with the RT technician(s) present.

d. Identify the radioisotope or x-ray source used.

e. Examine the radioisotope camera and accessories used.

f. Complete Table 26-5-11 in the Data Table section of this module. Table 26-5-11 contains all of the pertinent data to be collected regarding the RT method of NDE testing.

g. Prepare a short report on your visit.

DATA TABLE

The following tables are provided for the support of Exercise #8, #9, and #10 presented in this Module. Refer to the Procedures section for further details involving their use.

Table 26-5-9

Radiation Detection and Measurement Equipment

Date: _____

Site Visited: _____

_____

Personnel Met: _____

_____

_____

_____

Type of Detector Used	Range of Operation	Type of Source Used	Type of Radiation Detected

Table 26-5-10

X-ray Equipment Examination and Use

Date: _____

Site Visited: _____

_____

Personnel Met: _____

_____

_____

_____

X-ray Machine Type: _____

_____

X-ray energy: _____

Type of Photographic film used: _____

Recommended dosimetry: _____

Personnel Precautions: _____

_____

_____

Calculated permissible "stay-times" in radiation areas identified: _____

Effect on shielding usage specified: _____

_____

Table 26-5-11

Radiographic Test Site Visit and Inspection

Date: _____

Site Visited: _____

_____

Personnel Met: _____

_____

_____

Type of specimens to be radiographed: _____

_____

Source and film selection orientation and method of placement: _____

_____

Penetrameter selection and usage: _____

_____

_____

Specimen identification method: _____

_____

Overlap and number of exposures: _____

_____

Type of shielding employed: _____

_____

Use of screens and filters: _____

REFERENCE MATERIALS

Eastman Kodak Company. Radiography in Modern Industry, 1969

McGonnagle, Warren J., Nondestructive Testing, New York: McGraw Hill Book Company

Metals Handbook, Volume 11, Nondestructive Inspection and Quality Control, American Society for Metals

McMaster, Robert C. (ed.), Nondestructive Testing Handbook, New York: The Ronald Press Company

Overman, Ralph T., Basic Concepts of Nuclear Chemistry, New York: Reinhold Publishing Corporation

TEST

1. Complete the following statements:

   a. The movement of subatomic particles through space is known as _____.

   b. The movement of short electromagnetic waves of energy with the speed of light is known as _____.

   c. Two particles which are emitted from radioactive materials and have limited penetrating ability are _____ and _____.

   d. Two types of electromagnetic radiation which are used for radiographic testing are _____ and _____.

   e. Two types of gamma ray sources which are by-products of neutron bombardment are _____ and _____.

2. Indicate True or False for the following statements:

____ The "half-life" values of radioisotopes decrease with time.

____ The specific activity of source materials has no relation to resultant source size.

____ The specific activity of source materials may be measured in units of Curies per gram.

____ Short half-life is an undesirable quality for source material.

____ Radioactive source materials are encapsulated to permit safe and convenient handling.

____ Isotope cameras are never used for storing radioactive sources.

3. Select the correct answers to the following questions:

   a. What target material is most commonly used in X-ray tubes?

   (1) Uranium

   (2) Tungsten

(3) Sodium
(4) Aluminum

b. In an X-ray tube, a thermal conducting metal rod would be used for what?
(1) to heat-up the tube.
(2) to support the tube.
(3) to support the specimen.
(4) to remove heat from the target.

c. The duty cycle for any X-ray machine is dependent upon what?
(1) voltage and amperage.
(2) anode cooling.
(3) cathode deterioration.
(4) shielding thickness.

d. "Characteristic X-rays" are peculiar to what?
(1) the target material.
(2) the cathode.
(3) the velocity of the electron's.
(4) the specimen material.

e. A Cobalt-60, 20 Curie gamma source is obtained for radiographic use. What is its emissivity, measured at 1 foot?
(1) 29 R/Hr.
(2) 20 R/Hr.
(3) 200 R/Hr.
(4) 290 R/Hr.

4. Indicate True or False for the following statements:

____ Radiation dose rate is measured in curies.

____ Dosimeters measure dose rate directly.

____ The PIC dosimeter frequently has a scale graduated from 0-200 mR.

Before they are used to measure total radiation dose, dosimeters are "zeroed" by grounding or discharging the electrode or charging rod.

5. Select the correct word in the following statements:

a. Radiographic film density (increases) (decreases) proportionally with radiation exposure.

b. TLD's are (inferior) (superior) to film badges in recording whole body radiation exposure.

c. Radiation intensity in an area may be measured quickly with (TLD's) (survey meters).

d. Radiation survey meters operate on the principle of (ionization) (photoelectric effect).

6. Complete the following statements:

a. The accuracy of most radiation survey meters as about _____.

b. Survey meters which operate on the "gas amplification" principle are known as _____.

c. Geiger counters are inherently _____ sensitive than ionization chamber instruments.

d. A _____ of known intensity is used to calibrate radiation survey meters.

7. Fill in the blanks in the following statements:

a. Penetrating external radiation from X- or gamma ray sources is measured in _____ units.

b. The unit of penetrating radiation as applied to the exposure of human or animal tissue is the _____.

c. The biological effectiveness of fast neutrons absorbed by human tissue is _____ times as great as X-radiation.

d. Federal Regulations prohibit whole body exposures to penetrating radiation in excess of _____ per calendar quarter.

e. In a constant radiation field, the amount of absorbed radiation is _____ to the time exposed.

8. Given a 20 curie Iridium-192 source,
   a. what is the radiation dose rate at 1 foot?
   b. what is the dose rate at 10 feet?
   c. if a technician works at a distance of 10 feet from the source for 6 minutes, what dose will be receive?
   d. if the technician works at a distance of 15 feet from the source for 6 minutes, what dose will he receive?

9. Given a 50 curie source of Cobalt-60,
   a. what is the radiation dose rate at 1 foot?
   b. at what distance from the source will the dose rate be less than 100 mR/Hr?
   c. what is the radiation dose rate at 100 feet?
   d. at a distance of 100 feet from the source, how long may a technician work without receiving a radiation dose over 20 mR?

10. A radiation source of Cesium-137 is producing a radiation intensity of 1000 mR/Hr. To reduce the intensity to a safer working level of 125 mR/Hr., what thickness of shielding material is required to be placed between the source and the work area for:

    a. lead?

    b. steel?

11. The radiation intensity in an area is 400 mR/Hr, as emitted from a 200 kV X-ray tube. To reduce the intensity to 50 mR/Hr, what thickness of shielding material is required for:

    a. lead?

    b. concrete?

12. Indicate true or false for the following statements:

____ In radiographing an object, all rays emitted from the radiation source pass through the object and strike the film.

____ The object being radiographed must be placed close to the radiation source to minimize image enlargement.

____ In a radiograph, the "penumbra" is the image on the film representing geometric unsharpness.

____ The size of the radiation source has little effect on the sharpness of the resulting radiograph

____ The enlargement of the discontinuities in an object being radiographed increases as the source is moved further from the object and the film.

13. Select the correct answers in the statements as indicated:

a. Film image distortion can be minimized by making sure the radiation beam is _____ to the film.

(1) parallel
(2) behind
(3) perpendicular
(4) oblique

b. Film image distortion may interfere with _____.

(1) interpretation
(2) exposure time
(3) subject arrangement
(4) sensitivity

c. Geometric unsharpness is not affected by _____.

(1) source size
(2) source-to-film distance
(3) object-to-film distance
(4) exposure time

d. The intensity of the rays emerging from an object being radiographed varies with the _____ of the object.

(1) thickness
(2) density
(3) shape
(4) all of the above

14. Select the correct word in the following statements:

a. An image cannot be observed on a radiograph without adequate (density) (contrast).

b. Image sharpness on a radiograph is expressed as (definition) (subject contrast).

c. Film exposure is (greater) (less) at thicker areas of the object being radiographed.

d. Film contrast (is) (is not) affected by film density.

e. Differences in film density, as interpreted from a film "H & D" curve, are measures of (film contrast) (film speed).

15. Indicate true or false for the following statements:

____ Radiographic films should be exposed for the lowest practicable density to maximize film contrast.

____ Low speed films exhibit better grain and resolution characteristics than fast films.

____ Reversal may occur as a result of over exposure.

____ Film developing is not affected by temperature.

____ Stop bath solutions are used to save rinse water.

____ The action of the fixer solution, in the developing process, softens the gelatin on the film to improve flexibility.

____ Automatic film processors minimize manual handling of film and usually process film in less than 15 minutes.

16. Indicate true or false for the following statements:

____ Fluorescent screens are always used in high energy radiography for image intensification.

____ Metals with high atomic numbers are usually preferred for use as filters.

____ Scatter radiation may be limited with the use of masks and shields.

____ Penetrameters provide accurate measurements of film sensitivity.

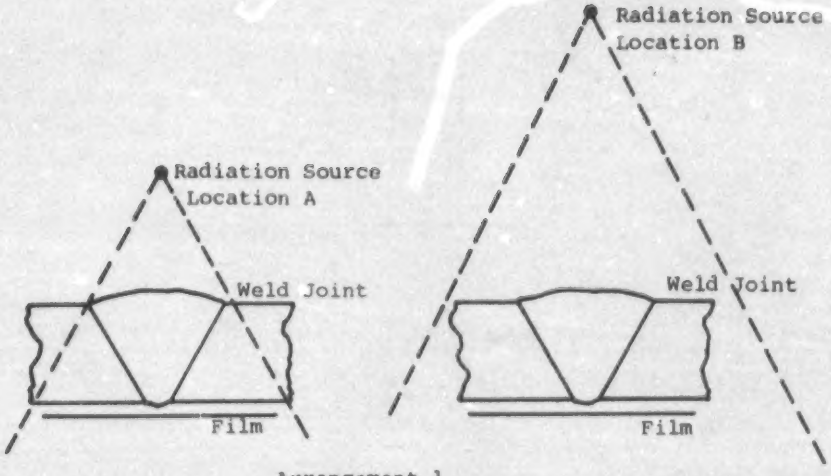
____ ASME Penetrameters provide for 3 different quality levels of inspection.

17. In radiography a 2" thick specimen, an ASTM 2-1T penetrameter as selected by the technician, and an acceptable radiograph was obtained. In the test situation,
    a. what is the thickness of the penetrameter used?
    b. which hole (or holes) in the penetrameter are visible?
    c. what is the diameter of each penetrameter hole?
    d. what is the equivalent penetrameter sensitivity?

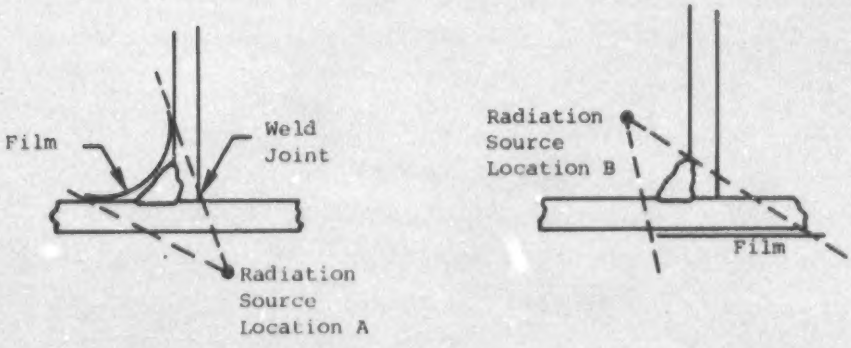
18. In radiographing a 1 1/2" thick weld joint, an equivalent penetrameter sensitivity of 1.0% was desired.
    a. what is the designation of the required penetrameter?
    b. what is the thickness of the penetrameter?
    c. what is the diameter of the smallest perceptible hole in the penetrameter?

19. For the radiographic exposure arrangements shown below, indicate which source location produces (1) minimum exposure time, and (b) minimum image distortion.

Arrangement	Radiation source location	
	Min. Expos. Time	Min. Distortion
1		
2		

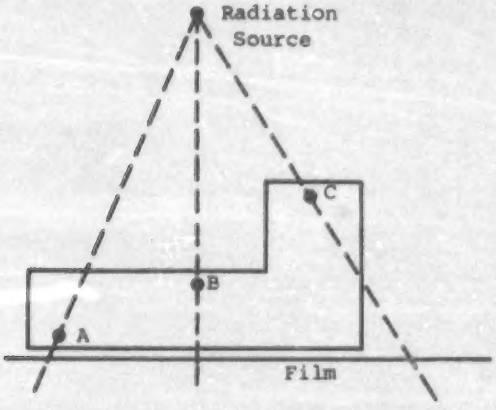


Arrangement 1



Arrangement 2

20. In the radiographic arrangement shown below,
(1) which of the projected images of defects A, B, or C will be in sharpest focus? _____
(2) which of the images (A, B, or C) will have the greatest distortion? _____



21. Mark the following statements true or false as applicable:
____ With only a single radiograph, it is impossible to establish the location of a discontinuity observed in a superimposed image of a circumferential weld joint.
____ Increasing the source-to-film distance also increases exposure time.
____ Definition is usually improved when the source-to-specimen distance is increased.
____ A panoramic exposure of a large pipe circumferential weld may be made with the film placed on the inside surface of the pipe.

____ Increased exposure time, in radiographing an object with a large range of contrast, compensates fully and obviates the need for multiple exposures.

____ Small pipe welds may be radiographed successfully with a panoramic exposure, with the radiation source located inside the pipe.